Journal
of
The Franklin Institute
Devoted to Science and the Mechanic Arts

Vol. 221 FEBRUARY, 1936 No. 2

THE PREPARATION OF POLONIUM SOURCES FROM RADON BULBS.

BY

L. R. HAFSTAD, Ph.D.,

Department of Terrestrial Magnetism, Carnegie Institution of Washington.

A detailed description is given of the technique developed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for the production of strong pure polonium sources by the method of I. Curie. Contrary to current opinions in this country, this method is neither difficult nor tedious. A complete double purification of the RaD from Radon bulbs can be carried out in several hours a day on four or five successive days. A recent source produced by the author had a surface-density of 30 millicuries per square centimeter, with 95 percent. of the particles having ranges greater than 3.57 cm. according to measurements made by E. Pollard at Yale University.

A. INTRODUCTION.

In recent years the wide interest in nuclear-disintegration studies has led to a great demand for strong polonium sources. While several methods for producing such sources are known,[1] the descriptions given in the literature usually assume either a familiarity with chemical manipulations or else access to equipment quite beyond the immediate reach of many physicists who are otherwise in a position to carry out observational programs of considerable value. After experiencing much

[1] I. Curie, *J. chim. phys.*, 22, 471–487 (1925); O. Erbacher, *Zs. physik. Chem.*, A, 156, 147 (1931); E. Rona and E. A. W. Schmidt, *Wien, Sitz Ber. Ak. Wiss.*, 2a, 137, 103–115 (1928).

(Note—The Franklin Institute is not responsible for the statements and opinions advanced by contributors to the JOURNAL.)

difficulty in early attempts,[2] the writer has now developed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington technique to such an extent that several sources of greater than 10 mc. have been produced.*

B. CONTAMINATION.

In the preparation of even the weakest sources great care must be taken to avoid contamination of laboratory apparatus. This point cannot be over-emphasized, for in any radioactive measurement the significant data are always the ratios of the effects being studied to the residual effects which are observed. As a result, an increase in source-strength results in little gain if the residual effect (contamination) is increased in the process. A droplet of even the weakest radioactive solution on the jaws of a pair of pliers, which is in general use, will spread to all other tools in the laboratory and is quite sufficient to cause a marked increase in the residual effect in any ionization-chambers, counters, or cloud-chamber assembled at any subsequent time. A strong source may emit as many as 10^9 alpha-particles per second, whereas a contamination giving as few as 10 particles per hour on the inside of an ionization-chamber would be fatal to many experiments.[3]

An even more insidious contamination-process arises from the fact that a strong radioactive source ejects recoil-aggregates in considerable numbers and these form secondary sources even on material which has never been in actual contact with a radioactive source. A piece of paper above which a source has been left standing for some time, for instance, will be found to be strongly infected.

These examples illustrate sufficiently the care which must be taken to avoid contamination and suggest that to a large extent all apparatus used in preparing and manipulating

[2] L. R. Hafstad, *Phys. Rev.*, **44**, 201–213 (1933).

* A recent source prepared for Pollard was measured by him at Yale University and found to have the following characteristics: Strength $= 23.5 \pm 1$ mc. on a 1-cm. diameter disc giving a surface-density of about 30 mc./cm.^{2} The source, while slightly tarnished, was relatively clean, 95 per cent. of the particles having ranges greater than 3.57 cm.

[3] H. Pose, *Zs. Physik*, **67**, 194–206 (1931); J. Chadwick, *Proc. R. Soc.*, A, **136**, 692–708 (1932).

sources must be segregated from the rest of the laboratory. Herein arises one of the chief difficulties in the preparation of sources. Any apparatus once used near radioactive material is irretrievably lost to the rest of the laboratory. Except in the most generously equipped laboratories, the best apparatus is usually not available under these conditions and improvised apparatus must be used to a large extent. In this article such practical working conditions will be assumed.

C. SOURCE-STRENGTH.

In estimating requirements and source-strength to be expected from a given radium-supply, the conversion-factors and tables given in this section will be found useful.

In the literature numerous units are used which are sometimes confusing to a beginner. Exact definitions may be found in the Report of International Radium Standards Commission,[4] but for convenience it is advisable to memorize the approximate relations 1 mc. = 1 mg. = 1300 E.S.U. = 3.7×10^7 alpha-particles per second. This will permit a rapid comparison of the source-strengths used by previous workers in the field.

An equally important question is that of estimating the source-strength which can be confidently expected from a given quantity of dead radon bulbs. The quantity of RaD in the bulbs can be estimated if the quantity of radium in solution from which the radon is obtained, and the fraction which is actually transferred to the bulbs or needles which are to be used, is known. (Often a fair fraction of the radon is used in gold "seeds" from which RaD cannot be conveniently extracted.) A convenient unit to use in estimating the strength of an available supply is the "gram-year" yield from radium. For instance, if it is known that the radon from one gram of radium is being introduced into bulbs each day, then from the transformation formula [5] one calculates the number of radon atoms in each bulb. Since each radon atom decays rapidly into an atom of RaD of long life, one can assume that after several weeks all have been converted

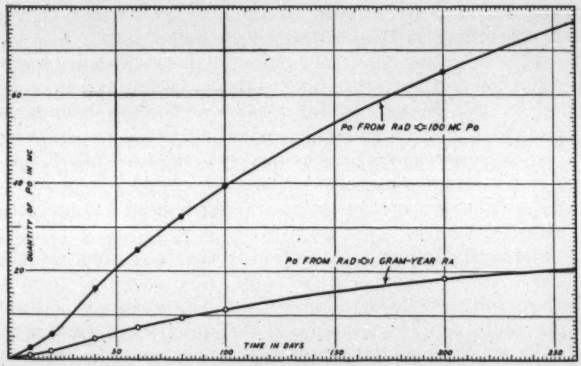
[4] *Rev. Modern Phys.*, 3, 427–445 (1931).

[5] E. Rutherford, J. Chadwick, and C. D. Ellis, "Radiations from Radioactive Substances," p. 11 (1930).

into RaD. This in turn decays into RaF, finally reaching an equilibrium such that 1 gram-year Ra ≅ 60,000 mc. Rn ≅ 28.7 mc. Po.

It must be emphasized, however, that this is the quantity which will be in equilibrium after a sufficient time has elapsed; for the case of RaF, this time is *two years*. Since it is only in laboratories where large quantities of material are available that solutions can be allowed to grow to their maximum strength, the curves in Fig. 1 are given to estimate the

FIG. 1.



Growth of polonium from RaD.

quantity of RaF present in a solution of RaD at any time after the RaF has once been completely removed. The values given will be further reduced by the efficiency of deposition factor which according to Joliot [6] is about 80–90 per cent. for densities up to 75 mc. per cm.^{2} but drops to 25 per cent. for densities of 600 mc. per cm.^{2} The curves have been recalculated using the latest official values [4] of the constants involved.

D. DISCUSSION OF DIFFERENT METHODS.

Comprehensive discussions of the various methods of preparing polonium sources from the chemist's point of view

[6] *J. chim. phys.*, **27**, 119–162 (1930); **28**, 201–205 (1931).

have been given by Erbacher and Philipp.[7] For a physicist, however, interested primarily in obtaining a source with the least possible delay for use in disintegration-studies, the factors involved in the choice of method will often be differently weighted.

In most cases the amounts of special auxiliary apparatus required in preparing sources will be the determining factor. In the order of simplicity the standard methods may be roughly classified as follows: (1) Chemical deposition without purification; (2) electrical deposition without purification; (3) chemical deposition with chemical purification; (4) electrical deposition with electrical or chemical purification and potential adjustments.

Method (1) will in general only give weak and impure sources but may with care produce quite satisfactory results if very strong sources are not required.[8, 9, 10] However, while such sources are satisfactory for survey work, the more exacting requirements of modern disintegration-problems will frequently require either stronger or cleaner sources than can be produced in this way.

Method (2) is particularly appealing to a physicist, who is usually more familiar with electrical than with chemical apparatus. Unfortunately, however, only comparatively low surface-densities of polonium are attainable by this means.[7] While Chadwick[11] has obtained sources up to 25 mc. of polonium per cm.^{2} by this method, a number of trials made by the writer with solutions which should have contained as much as 25 mc. of polonium * gave sources of only about

[7] O. Erbacher and K. Philipp, *Zs. Physik*, **51**, 309–320 (1928); O. Erbacher, *Naturw.*, **20**, 390–393 (1930); O. Erbacher, *Zs. physik. Chem.*, A, **165**, 421–426 (1933).

[8] E. C. Pollard, *Leeds Proc. Lit. Phil. Soc.*, **2**, 324–330 (1932).

[9] T. Bjerge, *Zs. Physik*, **89**, 277–282 (1934).

[10] M. D. Whitaker, W. Bjorksted, and A. C. G. Mitchell, *Phys. Rev.*, **46** 629–630 (1934).

[11] J. Chadwick and J. E. R. Constable, *Proc. R. Soc.*, A, **135**, 48–68 (1932).

* The radon bulbs from which the polonium was extracted were obtained through the generous coöperation of the following institutions and individuals: Dr. C. F. Burnham and Dr. F. West, Kelly Hospital, Baltimore, Maryland; Dr. G. Failla, Memorial Hospital, New York, New York; Dr. J. L. Weatherwax. Philadelphia General Hospital, Philadelphia, Pennsylvania; Dr. M. C. Reinhard, State Institute for the Study of Malignant Disease, Buffalo, New York; Dr. Carl

3 mc. per cm.^{2}, with relatively large amounts of RaE present as an impurity. It would appear, therefore, that strong sources are at least not readily attainable by this method.

The combination of electrical deposition on platinum with concentration by the method of Rona and Schmidt [1] gives densities as high as 110 mc. per cm.^{2}, but very special equipment is required. This latter method (volatilization in hydrogen) has the further disadvantage of tending to increase the number of "natural H-particles" from the source.

In the hands of Erbacher and his colleagues, method (4) has given excellent results and represents an ideal toward which one should work. Unfortunately, both highly specialized technique and complicated apparatus are required,[12] making it unsuitable for one who is primarily interested in the immediate use of a source rather than in its preparation. For such a one, another weighty factor against this method is the fact that it is only RaD which is first obtained in the pure state so that any polonium present in the original solution is lost unless one resorts to chemical purification.

After preliminary trials of all the methods, the writer has concluded that method (3), the chemical purification of I. Curie [1] with chemical deposition, is the most suitable for one who expects to make a source only once in several months, and therefore with the smallest possible amount of special equipment. When correctly carried out, this method is neither tedious nor time-consuming. The writer now carries through the entire process in one or two hours a day on several successive days, the exact time depending mainly on the number of beta-ray measurements made.

E. MEASURING APPARATUS.

It may be safely assumed that most of the troubles which are experienced in attempting to carry through a purification procedure arise from minor omissions or changes in the tested procedures outlined in the literature. Many such changes,

E. Nurnberger, University Hospitals, Minneapolis, Minnesota; Dr. Otto Glasser, Cleveland Clinic Foundation, Cleveland, Ohio; and Dr. Roscoe W. Teahan, Jeanes Hospital, Philadelphia, Pennsylvania.

[12] O. Erbacher, K. Philipp, and K. Donat, *Physik. Zs.*, **30**, 913–918 (1929); *Zs. physik. Chem.*, A, **156**, 142–149 (1931).

however, may be required by a lack of proper equipment. This lack is likely to be particularly acute in the case of radiation-measuring apparatus. Some items, however, are indispensable and will be discussed below in what appears to the writer as roughly the order of importance.

1. *Geiger Counter and Amplifier.*—Numerous descriptions have been given of this well-known piece of apparatus, and any of the various forms are satisfactory. Construction details for one form of counter are given by Bothe [13] and a circuit using American tubes is described by Johnson and Street.[14] The operation of the counter can be tested by a weak gamma-ray source (0.1 mg. Ra in glass) without danger of contamination until such a time as an alpha-ray source covered with a thin foil can be made. The counter and amplifier should be kept a safe distance from the radioactive material, and any tools or instruments used in the radioactive work, as well as the hands of the worker, should be tested for contamination before being allowed to enter the measuring laboratory.

2. *Zinc-Sulphide Screen.*—This simple accessory is essential in testing residues, etc., for alpha-particle activity, and with a little practice the user is even able to make rough estimates of source-strengths merely by the intensity of the fluorescence produced on the screen. The form used at the Department of Terrestrial Magnetism by the writer is shown in Fig. 2. The screen itself is made by dusting zinc-sulphide powder on a glass plate which is covered with a thin film of alcohol.

3. *Apparatus for Measuring Final Polonium Source-Strengths.*—While an alpha-particle electroscope suggests itself for this purpose, it must be borne in mind that with strong sources greatly misleading results are often obtained unless very special precautions are taken to ensure saturation.[15] Also, in disintegration-studies it is not total ionization but the number of particles of full range which is of importance. For these reasons it is probably safest, as well as simplest, to

[13] W. Bothe and H. Becker, *Zs. Physik*, **66**, 289–306 (1930).

[14] T. H. Johnson and J. C. Street, J. FRANK. INST., **215**, 239–246 (1933); Bennett, Stearns, and Overbeck, Rev. Sci. Inst. **4**, 387–390 (1933).

[15] G. Ortner und G. Stetter, *Physik. Zs.*, **35**, 563–564 (1934).

count the particles of various ranges in a given small solid angle [11] either by scintillations, by a Geiger counter, or better by a linear amplifier. If a Geiger counter is used, care must be taken to eliminate beta-rays by a magnetic field in order to avoid false results.

The writer uses a small-diameter glass tube 150 cm. long with a brass plug containing a 0.3-mm. hole (No. 80 drill) covered with mica of about 1-cm. stopping power at one end. The source-holder is screwed into an iron cylinder which may be moved towards or away from the window by a magnet. To eliminate the effects of contamination on the walls of the tube or on the face of the window, measurements are made with the source in place and then removed, other conditions

FIG. 2.

Zinc-sulphide screen.

remaining the same. The glass tube and its window are replaced as soon as any contamination is evident.

While the amount of polonium in a solution may be determined by the "method of the drops" described by Curie,[1] this information is mainly of importance to those who are studying the efficiencies of different methods of deposition. To those concerned with the use of a source rather than the process of its production, apparatus for the measurement of polonium in solution may be eliminated.

4. *Beta-ray Electroscope.*—It has been found convenient to use the form of chamber described by I. Curie.[1] With this chamber "1 mc. of radon at 40 cm. gives an ionization-current of 0.064 E.S.U." From relations given in section (*C*) we may convert to a more immediately useful relaton, namely,

the amount of RaD which, when equilibrium is reached, will yield 1 mc. of polonium, will, when placed 40 cm. from the Curie ionization-chamber, give an ionization-current of 1.37×10^{-11} ampere. Any one of the numerous direct-current amplifiers described in recent American literature will easily cover the necessary range. A relatively inexpensive form of such an amplifier constructed by L. F. Curtiss [16] was used in this work.

F. CHEMICAL APPARATUS.

1. *Precautions against Contamination.*—It is essential that some specific space be set aside for radioactive chemistry and that all apparatus used in this connection be considered as dangerously contaminated. It is advisable to have a full-length rubber apron and a generous supply of rubber gloves which can be definitely assigned to this work. Any suspicions of serious contamination on the clothes should be tested with a Geiger counter before working in other parts of the laboratory. An observing laboratory in which radioactive work has not previously been done is a valuable asset which should be carefully guarded.

2. *Crucibles and Beakers.*—The essential point in obtaining strong sources is to keep the volume of solution small. Curie recommends the use of quartz crucibles not greater than 10 cc., while Erbacher refers to containers as small as 1.5 cc. and speaks of dissolving residues in "one or two drops" of solution. These are ideals to work toward but the writer has found it convenient to use 30-cc. and 15-cc. crucibles throughout the chemical purification as will be described below. Smaller crucibles may be used for the purified solutions during deposition. At least six quartz crucibles of 30 cc. or less should be available when attempting the Curie purification. It is taken for granted that ordinary chemical glassware is available in addition.

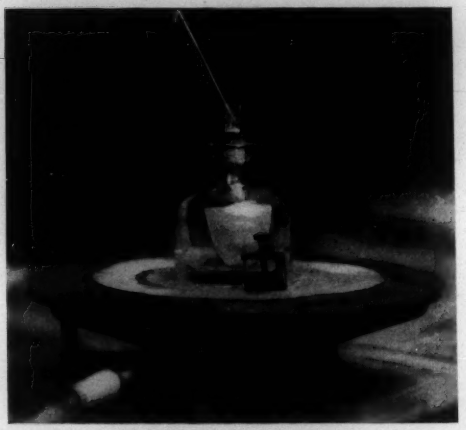
3. *Filters.*—Because of the large amount of glass in the radon bulbs which must be treated, it is impossible to keep the volume of solution small in the first stages. For this reason one fairly large "fritted filter-funnel" * is required.

[16] *Bur. Stan. J. Res.*, 10, 583–589 (1933).

* Jena fritted-glass filter-funnel 3G4, 30 ml., porosity 4, from Empire Laboratory Supply Company, 507 West 132d Street, New York, New York.

To reduce costs this may well be of glass since it is used before any chemical purification is done. The usual form of filter-flask is impractical in this work where one wishes to evaporate the filtrate and measure the radioactivity of the residue, so the upper half of an ordinary acid bottle placed over a bell-jar plate has been used in order to facilitate filtration by suction. In the latter stages of the purification an 0.8-ml. "fritted-quartz" filter-funnel (30aB4, porosity 4) is used with part of a smaller bottle as shown in Fig. 3. In the latter apparatus

FIG. 3.



Fritted-quartz filter, 0.8-ml. capacity.

particularly, the small bore of the filter-stem gives it a tendency to spatter, so care must be taken to insure that the stem projects into the beaker or crucible below and touches the side. Two 30-ml. fritted-glass filters and two 0.8-ml. fritted-quartz filters are recommended for this work.

4. *Evaporation-Apparatus.*—In order to insure against loss of active material, all filtrates must be evaporated to dryness and the activities of residues must be measured. Also in many cases it will be desirable to measure the activity of the

main solution, and hence this too must be evaporated. In this case particularly any spattering would result in serious losses as well as contamination of surroundings. For so many evaporations a steam-table or electric water-bath may be recommended but usually neither will be available under the conditions assumed in section (*B*). As a second choice two electric hot-plates, such as are readily obtainable, connected in series to operate at half voltage, are recommended. By placing several layers of asbestos paper above the heating element an adjustment can be obtained such that the temperature of a *dry* beaker or crucible will *not exceed 100° C.* As a further precaution, all beakers should be covered to prevent impurities from falling in. With such an arrangement the beakers may be safely left to evaporate overnight, and the program should be arranged to take full advantage of this possibility.

For some of the less exacting operations such as the concentration of large volumes of solutions obtained during recovery processes the writer has found it very convenient to use the evaporator described on page 21 of "Applied Inorganic Analysis" by Hillebrand and Lundell. A commercial form of this evaporator in monel metal may be purchased from the Central Scientific Company of Chicago.

5. *H_2S-Apparatus.*—Here again the desirability of open-mouthed containers to permit beta-ray measurements requires a somewhat unorthodox technique. By utilizing the top half of an acid bottle as shown in Fig. 4 it is relatively easy to introduce the H_2S under pressure and still keep the fumes out of the room.

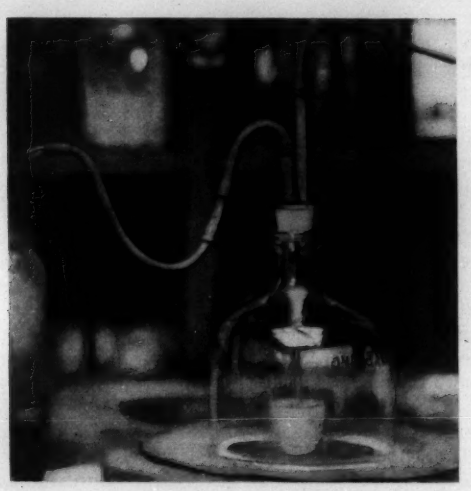
6. *Deposition-Apparatus.*—As a first approximation the writer has found the original Curie suggestion of rotating a metal disc in a solution by an extension of the axis of the fastest gear in an alarm clock to be quite satisfactory. It has been shown that faster rotation is an advantage,[17] however, so an 8-watt telechron motor geared to 60 revolutions per minute as shown in Fig. 5 is now used. Slightly higher speeds might be still better but much higher speeds [10] cannot be used with small volumes without danger from splashing. In Fig. 5 note particularly the hooked Pyrex-glass rod which

[17] I. Curie and F. Joliot, *J. chim. phys.*, **28**, 201–205 (1931).

is used to hold the foils during deposition (this will be referred to later).

7. *Sources and Source-Holders.*—It has been found a convenience to adopt a standard mounting for sources so that they may be readily interchangeable. This is shown in Fig. 6. By always depositing on thin foils the polonium from a number of old sources can be easily brought back into solution and redeposited on a new source; hence solid buttons are

FIG. 4.

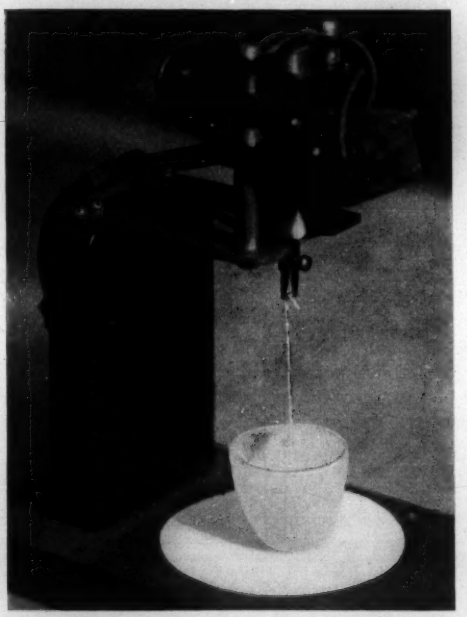


Hydrogen-sulphide precipitation-apparatus.

rarely used. It has been found that silver foil about 0.0004 inch thick is sufficiently strong to be handled conveniently and yet thin enough to be readily dissolved and precipitated without producing too large a volume of AgCl. (Such foil may be purchased from the American Platinum Works, Newark, New Jersey.) A special technique has been developed for mounting activated discs of this foil on the source-holders which probably should be described to save time-consuming experimentation.

With small volumes of liquid it is impracticable to immerse more than the foil itself during the deposition-process, and after deposition the foil cannot be conveniently handled. It is advisable, therefore, that the cementing compound be applied over one face before deposition. It will be found,

FIG. 5.

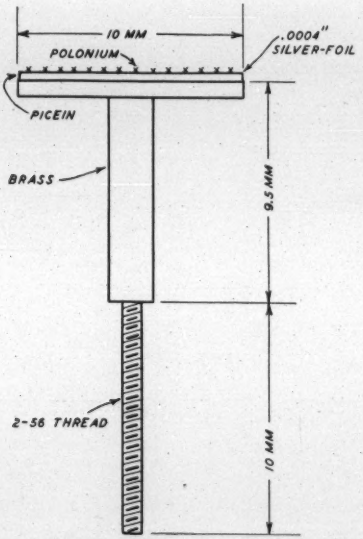


Telechron rotation-apparatus.

however, that the cement (picein is convenient) will have an awkward tendency to creep over the edges and on to the clean face of the foil. This can be circumvented as follows. The disc is pressed flat against a flat block of slate, or similar substance, for example, the top of a chemical table, a chip of picein is placed in the center, melted with a "pin-point"

gas flame and then "chased" to the edges, where it will be found to stop of its own accord. When cool the disc may be picked up by touching with the end of the glass hook previously mentioned. The picein backing will be found to give the stiffness necessary to prevent buckling during the rotation-process.

FIG. 6.



Standardized source-holder.

Again in removing the disc from the rod some trouble may be experienced unless it is done in the following manner. The disc with the rod attached is placed face down on a piece of clean paper. The back of the glass rod is touched gently with a warm piece of metal and in a few seconds the rod can be lifted without disturbing the foil. A source-holder de-

scribed above is then heated, the face coated with picein, and before it cools the foil is lifted with a pair of tweezers and allowed to "settle" into place on the face of the holder, the picein on the foil-disc being melted by the hot picein on the holder.

G. CHEMICAL PROCEDURE.

The chemical procedure of I. Curie is based on the fact that RaD, RaE, and RaF behave like their chemical analogues, lead, bismuth, and tellurium, and is essentially that of quantitative analysis for these elements. In the present case, however, it is desired to keep RaD, RaE, and RaF together throughout the entire process while removing in succession various elements which may be present as impurities.

The elements bismuth, lead, and tellurium all fall in group II with soluble chlorides but insoluble sulphides, and have the further common property that all may be precipitated from a dilute HCl solution by a slight excess of NH_4OH. Utilization of these two properties serves to separate the desired group from all metals except bivalent mercury. To eliminate this impurity Curie uses a modification of a procedure apparently due originally to K. Bülow [18] in which mercury is separated from lead by virtue of its solubility in potassium sulphide. Unfortunately tellurium sulphide is quite soluble and bismuth sulphide at least is somewhat soluble in alkali sulphides, and while in the presence of lead an insoluble lead tellurate should be formed, there is some danger of a loss of tellurium (RaF) if, to completely remove the mercury, too much of the alkali sulphide is used. On the other hand, if too little is used, some mercury will be left as an impurity and will disturb the critical electrochemical potential adjustment on which the actual deposition of pure polonium of high surface-density is dependent.

While a loss of RaE is annoying in that it upsets the control, it is not serious since it rapidly reforms from the RaD. If an accident occurs whereby the activity appears where it is not expected, it is advisable immediately to stop the work completely for several days, watching the activity of all residues carefully until it is clear which ones contain important

[18] *Zs. anal. Chem.*, 31, 697 (1892).

amounts of RaD. Failure to observe this precaution is likely to lead to the irritating situations in which an apparently large amount of carefully purified RaD evaporates into an insignificant amount of RaF, the measured activity being due to RaE alone instead of mixed with the RaD.

Losses of RaF (polonium) are at the same time more serious and more subtle. At best the measurement of a strong alpha-particle source is difficult, but when the active material is mixed with a relatively large amount of some solid residue a satisfactory measurement is practically impossible. For this reason it is difficult to state definitely the stages of the procedure in which the greatest losses occur and the precautions necessary to avoid these losses. The only simple guide is the zinc-sulphide screen which with practice will enable one at least to distinguish strong from weak sources and to follow the main part of the polonium through the purification-process. The precautions which can be advised are, therefore, only those used by chemists in manipulating tellurium compounds. Even here the analogy can easily be carried too far, for there is evidence that polonium behaves in some cases more like bismuth than like tellurium. If in spite of precautions an important amount of polonium is found in some residue, it is advisable to repeat the entire process after adding a very small crystal of lead nitrate (a fraction of a cubic mm.) since the procedure is based on the assumption that the presence of the lead will retain the tellurium as a precipitate under conditions when in the absence of lead it would be soluble.

The procedure outlined by Curie is as follows: (1) Digest crushed bulbs in aqua regia; (2) eliminate salts of copper and alkalies by adding NH_4OH; (3) filter; (4) precipitate group II by H_2S; (5) remove mercury by $KOH + (NH_4)_2S_x$; (6) dissolve residue with aqua regia.

As a rough indication of what may be expected on a first attempt at this procedure without complete and explicit directions, the beta-ray measurements on some of the writer's early efforts are given below. During these trials the volumes of the solutions were 100 to 200 cc., and NH_4OH and $(NH_4)_2S_x$ were taken from stock bottles.

Example 1, June 1932.—The activity of the original bulbs

was not obtained, so the activity of the sulphides is arbitrarily taken as 100 per cent. (the figures given are percentages).

Mortar and pestle after many washings	2.9
Crushed glass after many washings	1.2
Aqua regia beaker after many washings	11.0
NH_4OH beaker after many washings	2.3
NH_4OH filter-paper after many washings	8.0
H_2S beaker after many washings	0.6
Filter-paper and active sulphides	100.0
Ditto after $(NH_4)_2S_x + KOH$	44.0
Filtrate from above	21.0
Filter-paper after first aqua regia treatment	26.0
Second aqua regia treatment	15.0
Third aqua regia treatment	9.0
Fourth aqua regia treatment	6.0

While the lack of internal consistency in these readings is great enough to prevent them from being taken as more than an indication, two facts are clear: (1) The $[(NH_4)_2S_x + KOH]$ treatment carried away active material and (2) the aqua regia treatment of the sulphides left a large fraction behind.

Example 2, June 1932.—In this case the activity after the first NH_4OH precipitation is taken as 100 per cent. (the figures given are percentages).

Original bulbs	87
After NH_4OH treatment	100
After $[(NH_4)_2S_x + KOH]$ treatment	100
After second NH_4OH treatment	63
After second H_2S treatment	69
After second $[(NH_4)_2S_x + KOH]$ treatment	43
Later recovered from filter-paper, etc.	40

After consultation with chemists and the adoption of the procedure given in section I, the beta-ray readings run as follows:

Example 3, January 1934.—

Original bulbs	68
After H_2S treatment	77
After $[(NH_4)_2S_x + KOH]$ treatment	93
$[(NH_4)_2S_x + KOH]$ solution (evaporated)	9
Final source	100

Here again the readings cannot be taken at face value for at times the active material was in a small 0.8-cc. filter crucible,

at times it was spread over the walls of a relatively large beaker, thus giving different effects on the ionization-chamber. Large losses, however, are no longer occurring suddenly and unexpectedly as they did in Example 2.

H. DETAILED PROCEDURE FOR EXTRACTION OF POLONIUM FROM RADON BULBS.

In the procedure given below it will be assumed that one polonium source is desired as soon as possible in order to begin a preliminary set of observations. For this reason a relatively weak source is first prepared from those bulbs which are free of mercury; the rest are then carried through the complete purification-process giving a strong source at some later time. This procedure is to be recommended, for many steps in the process require leisurely evaporations or precipitations and should not be hurried. Such steps can be most effectively performed by allotting only a few hours per day to actual manipulations, allowing solutions to stand overnight for evaporations or precipitations.

In detail the steps are as follows:

Preliminary Source.—(1) Make certain that none of the bulbs contain radon itself in quantities which might cause gamma-ray or especially beta-ray burns. All bulbs should be at least one month old.

(2) Examine bulbs or needles individually (use forceps, avoid getting face too close) and separate into two groups, one comprising bulbs which are whole and which contain no mercury globules, the other containing all the rest.

(3) Thoroughly wash the selected first group in ether, alcohol, and distilled water to remove paraffin, grease, and other organic matter.

(4) Crush the bulbs in a well-ventilated place so as to avoid inhaling any radon which may remain. Do not grind extremely fine. (Fine grinding tends to bring more glass into solution as an impurity.) Transfer to a clean 100-cc. Pyrex beaker. This operation can best be done in a mortar containing some water to prevent escape of small particles. The method used at the Department of Terrestrial Magnetism is indicated in Fig. 7. With this arrangement heavy pressures may be applied with little danger of splashing provided they are applied gradually. With good luck a batch of bulbs may

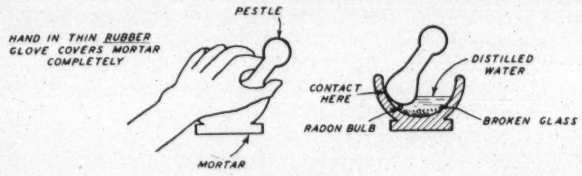
be crushed without any of the solution spattering on the hand. However, if it does, there is no serious harm done for washing the gloved hands with soap and water is effective in removing contamination. This must be tested with a point counter.

(5) Add HNO_3 to make the solution about $6N$ and heat nearly to boiling for some hours. This is most conveniently done on a steam-bath or on an electric hot-plate as described in section (*G*).

(6) Filter through a glass-fritted filter washing well with hot $6N$ HNO_3 and then with distilled water.

(7) Transfer filtrate to a 30-cc. quartz beaker. If the volume is too great to transfer 30 cc., then evaporate, and transfer 30 cc. more. In this way only the dilute radioactive solution is transferred and losses will be kept small. Evap-

FIG. 7.



Method of crushing bulbs.

orate to dryness (avoid spattering), add distilled water from wash-bottle washing down sides, and evaporate again. Measure beta-rays. Repeat the distilled-water process several times. This is important for the dilute HNO_3 concentrates by evaporation to a constant boiling mixture of about $15N$.[19] A residue from this acid would spoil the adjustment of the acid-concentration in the next step.

(8) Add 5 cc. of $0.1N$ HNO_3 plus two drops of $0.5N$ HCl; heat nearly to boiling for some minutes to make sure that all material is dissolved. The solution now contains a relatively large amount of RaD, RaE, and RaF.

(9) Cut a piece of silver foil about one square cm. in area, place on a piece of nickel sheet, and heat to red heat over a

[19] F. P. Treadwell and W. T. Hall, "Analytical Chemistry," 8th ed., 1, p. 60 (1932).

Bunsen flame. This will reduce any AgS present and will give a bright surface. When the silver has cooled sufficiently, pick it up by touching it with the picein-coated end of one of the thin glass hooks shown in Fig. 5.

(10) Now make ready two 30-cc. Pyrex beakers, one with $3N$ HNO_3, the other with distilled water. Dip the silver foil in the $3N$ acid and watch carefully for etching to begin. If nothing happens, warm the acid slightly. The bright surface of the silver will suddenly disappear and be replaced by the mottled surface of the separate metal crystals. The foil must be immediately withdrawn and washed carefully in the beaker of distilled water. The foil should now be transferred immediately to the warm radioactive solution, attached to the turning mechanism, and left for several hours. In removing, it should be withdrawn slowly, held above the beaker while it is rinsed with a few drops of distilled water from a small wash-bottle. The foil is tested for alpha-particles by a zinc-sulphide screen and the beta-ray activity noted.

(11) About 5 cc. of $6N$ HNO_3 is placed in a 15-cc. quartz crucible and heated nearly to boiling. The silver foil is immersed in this and is immediately dissolved. The glass rod is carefully rinsed in distilled water and is set aside for future use. Then $6N$ HCl is added to this solution, drop by drop, from a fine pipette until no further precipitate of AgCl appears.

(12) This beaker is left to stand overnight while the precipitate settles. (Do not try to hurry this step; after standing sufficiently long the precipitate forms a hard cake in the bottom of the crucible and decantation with a pipette or Pyrex medicine dropper is easily accomplished.) The clear solution is then transferred to a clean 15-cc. quartz crucible and evaporated to dryness to remove HCl. Add 10 cc. of $0.1N$ HNO_3, heat to nearly boiling to make sure all crystals are dissolved. This solution now contains a relatively large amount of polonium with a small amount of RaE present as an impurity.

(13) The polonium may again be deposited on silver and the above process repeated until a source sufficiently free from RaE is obtained. The final source should then be prepared and mounted as described in section (*G*-7).

Main Source.—The main solution of RaD is next prepared as follows:

(14) Measure the glass residue in the filter from step (6); it will be found to possess considerable activity. Transfer to the mortar and grind to a fine powder. Transfer to beaker previously used for digesting in HNO_3.

(15) Wash the second group of bulbs as in step (3), grind to a powder, and add to the glass from step (14). The beaker will contain perhaps 10 to 20 cc. of glass and 50 cc. of water. Add 10 cc. concentrated HNO_3, 10 cc. concentrated HCl, and heat to boiling, then evaporate (without spattering) to about 40 cc. Filter through a Jena glass-fritted filter-funnel into 100-cc. beaker. Wash glass on filter well with distilled water, and measure its beta-ray activity. If still appreciable (greater than 2 per cent. of the original), repeat the above treatment, using a slightly stronger acid solution and allowing to digest (warm) overnight if necessary to remove the activity. The writer's troubles have never been at this stage.[9]

(16) Transfer the filtrate from step (15) to a 50-cc. beaker and evaporate to dryness as in step (7). This evaporation is necessary to prevent the formation of large quantities of gelatinous $Al(OH)_3$ in the next step, for relatively insoluble aluminum salts are formed on exposure to air. Measure and record the beta-ray activity of the residue which will contain a relatively large amount of material. This is composed largely of salts of mercury and such metals as may be present in the mercury as impurities and also material due to the attack of the glass by the aqua regia. The beta-ray activity should in general be greater than the original measurement of the bulbs since the absorption of the glass has been eliminated. Add 3 cc. of $6N$ HCl, heat nearly to boiling, add 15 cc. of distilled water giving 18 cc. of $1N$ HCl, and heat for several minutes.

(17) Prepare a dilute solution of NH_4OH in a graduate by adding 3 cc. of about $15N$ NH_4OH as taken from a Ceresin bottle [20] to 12 cc. of water giving 15 cc. of about $3N$ NH_4OH. Add 5 cc. of this to the acid-solution of step (7), stirring well, and then add one drop at a time until no more precipitate

[20] W. F. Hillebrand and G. E. F. Lundell, "Applied Inorganic Analysis," p. 32 (1929).

forms. Add a few drops in excess and test by odor. Use caution because of beta-rays. Filter into a 100-cc. beaker. Wash the precipitate with about 20 cc. of water to which several drops of $3N$ NH_4OH have been added. Use not more than 5 cc. at a time and allow filter to suck dry before more water is added. Measure activity of precipitate on filter. Evaporate filtrate to dryness, label carefully, set aside, and measure activity of residue at intervals for about one month.

(18) Place 100-cc. beaker under filter. Pour through filter one cc. of boiling $6N$ HCl, 40 cc. of $0.3N$ HCl, and 20 cc. of water giving 60 cc. of $0.3N$ HCl. Measure activity of filter. Repeat acid-treatment if necessary, keeping track of the amount of acid added so that filtrate can be adjusted to $0.3N$ HCl. Add HNO_3 only as a last resort, but if this proves necessary to remove the activity use a separate beaker and evaporate to dryness before taking up in HCl. Heat the solution to boiling, begin passing H_2S through the solution while hot and continue while the solution cools. Leave the solution under H_2S pressure overnight.

(19) Decant most of large volume of the clear solution through a filter into a 200-cc. beaker without disturbing the residue, then shake up the residue and transfer to the filter. Rinse the beaker several times with water saturated with H_2S and pour through filter. Measure activity.

(20) Estimate volume of sulphides in cubic cm. This is principally mercury, so multiplying by 7 one obtains roughly the weight in grams of mercury present. For each estimated gram of mercury take ½ cc. of NH_4OH (Ceresin bottle) and 5 cc. of water giving roughly a 3 per cent. NH_4OH solution. Place in quartz crucible and saturate with H_2S, giving ammonium hydrosulphide according to the equation $NH_4OH + H_2S \rightleftarrows NH_4HS + H_2O$; about 30 minutes should be allowed for this process. When this solution is ready, but not before, take 2 cc. of water and ¼ cc. solid KOH for each gram of mercury present in the sulphides making a 20 per cent. solution of KOH, double this quantity to give excess specified by Curie and add to the solution of NH_4HS just prepared, giving the additional equilibrium $NH_4HS + KOH \rightleftarrows NH_4OH + HSK$. Heat this solution nearly to boiling and pour slowly through the sulphides left on the filter in

step (19). The insoluble mercury sulphide is converted into the soluble $Hg(SK)_2$ by the equilibrium $HgS + HSK + KOH \rightleftarrows Hg(SK)_2 + H_2O$, the excess KOH forcing the reaction to proceed from left to right.[21] Wash the residue in the filter with H_2S water and measure the beta-activity. If all is going well, the activity will be as high or higher than before while the amount of material on the filter will be vanishingly small.

(21) Place clean quartz beaker under filter and pour through filter several successive washes of hot concentrated acid, 10 cc. concentrated HCl plus 3 drops of concentrated HNO_3,* rinse with water, and measure activity; repeat until activity in filter is reduced to about one per cent. Evaporate filtrate to dryness, add several drops of concentrated HCl, evaporate to dryness again. Repeat this process several times to get rid of HNO_3, converting all salts to the chlorides.

(22) Dissolve residue in 10 cc. of normal HCl (heat slightly) and repeat steps (17) to (21). In step (18) it will be convenient to assume some arbitrary value for the amount of mercury present; this may be taken as one gram. On the completion of step (21) the second time the residue should be washed down from the sides of the crucible with distilled water and evaporated to dryness several times to eliminate excess acid. Finally dissolve in 5 cc. of $0.1N$ HNO_3 and 1 or 2 drops of $0.5N$ HCl.[6, 18] The solution is now ready for the deposition of the final strong source by the procedure of steps (9) to (13).

The writer wishes to thank Dr. L. F. Curtiss of the National Bureau of Standards for his continued interest and aid, and for permission to carry out this work in a room in his laboratory set aside for chemical manipulations of radioactive materials. The writer wishes especially to thank Dr. E. G. Zies and Dr. C. S. Piggot of the Geophysical Laboratory of the Carnegie Institution of Washington for invaluable advice on chemical procedure.

[21] F. P. Treadwell and W. T. Hall, "Analytical Chemistry," 8th ed., 1, p. 211 (1932).

* If concentrated aqua regia is used at this stage, there is danger of oxidizing the lead sulphide into the sparingly soluble $PbSO_4$ [see F. P. Treadwell and W. T. Hall, "Analytical Chemistry," 8th ed., 1, p. 221 (1932)]. This is what happened in example 1 of section (*G*).

"Marks" Polarizing Plates.—Formerly, plane polarized light has been produced and analyzed almost universally by means of the nicol prism. Such prisms are relatively expensive so that the advent of a considerably cheaper polarizing medium is certainly a welcome achievement. The single Marks polarizing plate consists of a glass plate, on one surface of which is a polarizing film. This film is an extremely thin coating adhering firmly to the glass face and light is polarized upon passing through it. Experiments show that Marks polarizing plates are approximately 45 per cent. transparent to ordinary light. When looking through two plates, the polarizing axes of which are parallel, they appear transparent (36 per cent. transmission) and colorless. When the axes are set 90° to each other, the plates appear black and transmit about 2 per cent. of the light impinging on the first plate. If carefully observed in this position of maximum extinction it will be noticed that the color is more nearly blue-black. Marks plates have proved to last indefinitely provided they are not heated above 75° C. and when unmounted are not exposed to excessively moist conditions and are not scratched by polishing the polarizing surface with a coarse material.

A Marks polarizing biplate consists of two single plates with their polarizing films adjacent the planes of polarization coinciding and a transparent medium placed between these films. A 120° cone of light may be passed through the aperture of a mounted biplate and polarization is equally effective at all angles of incidence. Compared with the 19° cone that is usual with the nicol prism, it is evident that far more light can be gathered from a given source by the biplate and the optical system may therefore be shorter.

The polarizing plates can be mounted ruggedly. They may be freely handled by students and lend themselves suitably to classroom and laboratory demonstrations of polarized light phenomena and their applications in science and technology.

C.

"The accidental observation made in a Chicago greenhouse, that one part of illuminating gas in 80,000 parts of air caused carnations to 'go to sleep' led to the discovery of ethylene as an anesthetic."—T. A. Boyd, "Research."

VACUUM PUMPS AND PUMP OILS.* PART I. SOME FRACTIONATION PUMPS.

BY

K. C. D. HICKMAN.†

Twenty years after the invention [1] of the simple and elegant condensation pump, it would seem superfluous to offer a lengthy study [2] of its operation were it not that the introduction of new working fluids [3] has banished much of the original simplicity and has led to contradictory and often disappointing results. Misleading statements have appeared in the literature; and the claims, in particular, advanced for butyl phthalate [4] by the author and his disparagement of the hydrocarbon oils, later marketed as Apiezon *A* and *B*,[5] require drastic qualifications.

THE PROBLEM.

It has been assumed since 1915 [6] that the lowest pressure that can be attained by a vapor pump should correspond with the vapor pressure of the working fluid in the coldest part of the high vacuum side of the system. With mercury on a summer day, and in the absence of a special cooling trap, this proves to be about 5×10^{-3} mm., agreeing well with theory. With organic fillings having vapor pressures at room temperature varying from 10^{-4} to 10^{-8}, corresponding limits are seldom, if ever, reached—why?

Before hazarding an answer, it is well to examine the

---

* The new constructions and pump oils described in these papers are the subject of patent applications.

† Communication No. 569 from the Kodak Research Laboratories.

[1] L. Langmuir, J. FRANK. INST., 1916, **182**, 719; U. S. Pat. 1,393,550; etc.

[2] W. Gaede, *Zeit. für. Tech. Physik*, 1923, **4**, 337.

[3] C. R. Burch, *Nature*, 1928, **122**, 729.

[4] K. Hickman and C. R. Sanford, *Rev. Sci. Inst.*, 1930, **1**, 140.

[5] Manufactured under Metropolitan Vickers patents and marketed by Shell-Mex Ltd., London.

[6] W. Gaede, *Ann. der. Physik*, 1915, **46**, 357.

experience of others with the two best known alternatives to mercury, namely, Burch's hydrocarbon oils and our *n*-dibutyl phthalate. The former have a real vapor pressure of 10^{-6} mm. to 10^{-8} mm. and the latter 2×10^{-4} mm. at summer room temperature,* the limits being, perhaps, five times lower when the liquids are boiled in inverted or "mushroom" pumps, surrounded with cooling water at winter temperatures.

Becker and Jaycox,[7] while able to secure vacuums of 10^{-6} to 10^{-8} mm. with their ingenious charcoal trap, obtained only 10^{-2} to 10^{-4} mm. with the pumps alone and apparently there was no significant difference between the oils despite their different volatilities.

Estermann and Byck [8] obtained high efficiencies with mercury in a large glass and metal pump and when they transferred to oil fillings, they reported pressures down to 10^{-6} mm., but their readings, made with the McLeod gauge, are open to suspicion. In the writer's own early work, zero readings of 10^{-6} mm. have been obtained repeatedly with a McLeod gauge, and it was not until a carefully calibrated Pirani gauge and later an ionization gauge was included in the system that a real pressure of 5×10^{-4} mm. was found to exist.

Von Brandenstein and Klumb [9] were able to secure a vacuum of 10^{-5} mm. again and again with butyl phthalate, but dismissed Apiezon oil as too difficult to degas! Contrast this with the statement made to the author that phthalate is "worthless as a vacuum agent, and we are abandoning it in favor of Apiezon oil with which we can secure pressures as low as 10^{-8} mm. without a trap." The present work was prompted by this last criticism. Recently, a two-stage pump has been described which employs Apiezon oil *B* against a backing pressure as high as 0.2 mm. Vacuums of 10^{-5} mm. and 10^{-8} mm. are claimed.[10]

---

* Exact temperature and pressures are being avoided in this section of the paper in view of what follows.

[7] J. A. Becker and E. K. Jaycox, *Rev. Sci. Inst.*, 1931, **2**, 773.

[8] I. Estermann and H. T. Byck, *Rev. Sci. Inst.*, 1932, **3**, 482.

[9] M. von Brandenstein and H. Klumb, *Physikalische Zeit.*, 1932, **33**, 88.

[10] J. E. Henderson, *Rev. Sci. Inst.*, 1935, **6**, 66.

THE MECHANISM OF PUMPING WITH AN OIL VAPOR.

A key to these varying experiences was furnished to the author by C. R. Burch, the inventor of the oil-operated condensation pump, in a letter received early in 1932.* Later, a patent specification appeared † containing the paragraph: "Another object of the present invention is to provide a pump possessing improved powers of eliminating from itself and passing into the fore vacuum *substances which are present in its working fluid as impurities which are produced in its working liquid by thermal decomposition or by the penetration of an electric discharge into the working fluid or its vapour, or which enter the pump from the system under exhaust or are present for any other reason, the said substances being of greater volatility than the working fluid,* but not necessarily being gaseous at the temperature of the room and at the pressure obtaining in the fore vacuum"; it is thus evident that Burch was fully aware of the condition which forms the subject of this paper.

The key is, then, to be found in the lack of homogeneity of the purest oil in comparison with mercury. Even the most carefully prepared organic fluid is likely to contain traces of lighter and heavier constituents which collect in the wrong

* ". . . Due to multiple collisions in the jet, oil molecules can leave the jet in the backwards direction without ever hitting the condensing tube. You thus get a stream (in our type 03 pumps this stream has a density corresponding to a pressure of about 10^{-3} to 10^{-4} mm. coming backwards), and hitting the part of the condenser tube immediately behind the jet . . . most of the 'reverse stream' strikes will be appreciably above room temperature, and (very slow) distillation will take place from it (in both directions), so that the surface from which oil milecules reach the gauge will be supplied, not with oil of the same composition as that in the boiler, but with the lightest constituents thereof, which have been concentrated by evaporation from the lukewarm surface. Thus, the limiting pressure of such a pump will be not the vapor pressure of the contents of the boiler, at room temperature, but that of what I believe an oil technologist would call 'light ends' from the contents of the boiler, fractionated by the lukewarm part of the pump mouth behind the jet. I have always regarded it as desirable to cool the condensing tube slightly below room temperature, i.e., to water-cool it so as to avoid this type of concentration of 'light ends' towards the system under exhaust. Similarly, I have felt it desirable to arrange the location of the fore vac pipe, and the heat conductance of the various parts of the pump so that the fore vac pipe runs lukewarm (even up to 50° C.) so as to aid in the elimination of volatile impurities into fore vac."

† C. R. Burch and F. E. Bancroft, B. P. 346,293, applied for January 6, 1930, accepted April 7, 1931.

places in the pump. The volatile bodies which spoil a vacuum diffuse into the high vacuum side and the more phlegmatic materials which could improve a vacuum remain uselessly in the boiler. The practical question to be answered is what is the degree of contamination of a reasonably pure fluid and how much does the contamination influence the vacuum?

The active portion of a pump fluid is a gas; the condensate on the walls and the liquid in the boiler are merely operating reserves. Thus, a large pump could contain half a liter of vapor of a molecular weight of about 300, working around a 1 mm. of mercury pressure and weighing, therefore, about 0.005 gram. If 10 per cent. of this vapor consisted of a more volatile fraction, the vacuum would be impaired, yet this quantity of impurity would be only 0.001 per cent. of a total pump filling weighing 50 grams. One part of an extra substance in 100,000 parts of an oil would not become partitioned so that all the impurity remained in the vapor. Nevertheless, when the boiling points are sufficiently separated, much of the impurity collects in the vapor. Evidence will be advanced that mixtures of widely separated boiling points do occur and that pumping fluids also accumulate considerable quantities of material boiling a few degrees lower than the main portion.

The compound with which the writer has had the most experience is *n*-dibutyl phthalate, and the argument will, therefore, center around butyl phthalate. It applies equally to the higher phthalates which, it is hoped, will succeed the butyl ester.

All the samples of "pure" butyl phthalate which have been prepared have contained traces of isomeric butyl phthalates boiling about 20° lower than the normal ester; of phthalic anhydride 30° lower; of water 250° lower; and air some 530° lower. During use, thermal decomposition may provide butyl alcohol, butylene [11] and carbon dioxide, all boiling some hundreds of degrees lower than the original phthalate. After prolonged use in a pump, less volatile polymers and tarry residues are formed which accumulate at the evaporating surface, raising both the real and apparent * boiling points of

[11] "Pyrolysis of Carbon Compounds," C. D. Hurd, A. C. S. Monograph, Chemical Catalog Monograph, 1929, page 555.

* By repressing evaporation.

the fluid. The temperature rises, accelerates decomposition and the spoiling proceeds in a vicious circle.

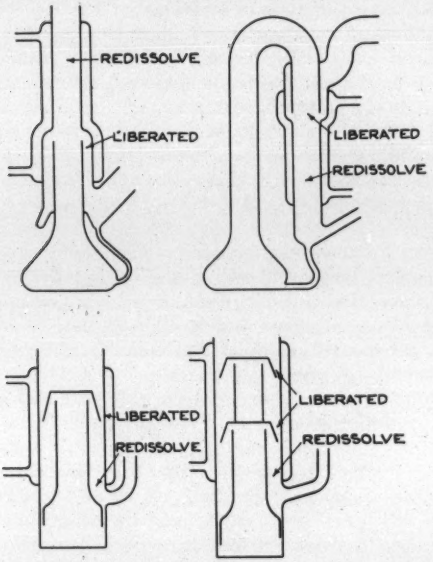
Pump oils other than butyl phthalate are not immune from these defects. The foreign bodies differ in kind but not in their action. The condition may be conventionalized by supposing that a pump fluid consists of a number of portions designated alphabetically from A to Z. The distribution of quantities in a "pure" homogeneous liquid, such as a phthalate ester, is roughly: $A + B + (C \cdots Y) + Z$ and in an oil of the Apiezon type: $A + B + (C + D$, etc., to $W + X + Y) + Z$.

Thus in the first example (butyl phthalate), A comprises the permanent gases and water vapor; and B the alcohols, phthalic anhydride or other "light ends"; the portion $C \cdots Y$ is homogeneous and has a boiling point of 104° C. at 0.1 mm. Hg. In the second example (Apiezon oil), the various constituents boil between 130° C. and 170° C. The harmful members are A, B, and Z in each case, though Z is of secondary importance and matters only if it contributes materials to A or B.

Consider what happens when an oil is boiled in a condensation pump, of which four usual types are shown diagrammatically in Fig. 1. In a short time, the constituents A and B, which spoil a high vacuum, are pushed to the point of highest vacuum (marked by the arrows), while the most useful pumping fluids—W, X, Y—remain inactive in the boiler. This is not all. A and B have been rejected by the hot vapor but both tend to contaminate the cold condensate as it returns to the boiler. A will redissolve only slightly, the quantity being directly proportional to the pressure maintained by the mechanical backing pump. B, however, will *redissolve completely* unless its *vapor pressure at the temperature prevailing at the pump exit is greater than the pressure maintained by the backing pump.*

It is the redissolution of constituent B which prevents the pump filling yielding its optimum vacuum. It will be seen presently that the rate of thermal decomposition of pump oils has been greatly exaggerated and is of importance chiefly because the effect is cumulative. The redissolution of vapors is most pronounced in the inverted type of pump, material

FIG. 1.



discharged at the top being re-absorbed at the bottom. The simple vertical pump, often so severely condemned because the warm condensate, falling backwards, limits the pumping speed, suffers least, the chimney forming a miniature fractionating column at the top of which the unwanted volatiles collect. Although continuously falling down the tube, the type *B* volatiles are re-evaporated by the ascending vapors and are kept away from the intake region. In considering the plausibility of this statement, it is well to remember that the continuous rejection is possible because the condensed volume of impurity is often *less than one drop*.

The favorite double-stage mushroom pump (Figs. 1–4) is a particularly gross offender with mixed oil fillings. The long central tube separates the $C - X$ portion of fluid, using C at the high vacuum jet and X at the low in the wrong sequence

but, since these pumps are designed to work against a higher backing pressure than the single-stage variety, the $A - B$ constituents are more thoroughly redissolved on the return journey.

A conclusion which might be drawn is that mixed oils should be abandoned in favor of single substances which have been extremely carefully purified. This conclusion would be erroneous, for the purest liquids alter during use, acquiring impurities, and the mixed oils of the Apiezon type have certain properties which will continue to recommend them. A better solution is to redesign the pumps so that the oil constituents will be separated in the proper order by a mechanism which will preserve continuous fractionation and purging. The design could converge in two directions, one resulting in a multi-compartment pump, the other employing a fractionating column to purify the liquid before reaching the jets.

Fortunately, the principle can be tested in a pump having only three compartments for separating the "pure" liquid from most of the higher and lower boiling substances.

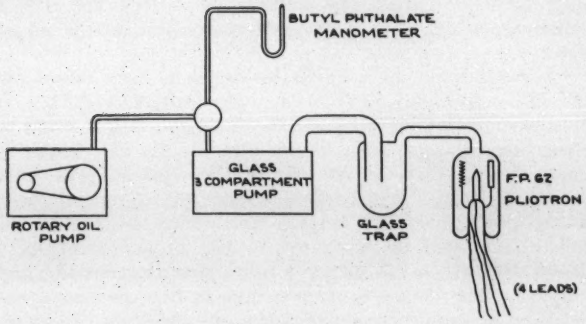
EXPERIMENTAL.

Before describing the three-compartment pump, it is necessary to define very clearly the conditions of measurement. Factors influencing the speed of pumping are well understood [12] and, except for a few pilot tests to verify that the speed has not been impaired by the fractionating features or absence of cooling associated with the present pumps, the measurements have been confined to determining the lowest pressures obtainable.

The experimental apparatus (Fig. 2) comprised a mechanical pump, a phthalate oil manometer [13] to measure the backing pressure, the fractionation pump under test, a cooling trap for occasional use, and an ionization gauge [14] for the high vacuum measurements. Because of the presence of readily condensible vapors, the McLeod gauge was considered unsuitable and was omitted. The current for the F. P. 62

[12] T. L. Ho, *Physics*, 1932, **2**, 386.
[13] K. Hickman, *Rev. Sci. Inst.*, 1934, **5**, 161.
[14] S. Dushman and C. G. Found, *Phys. Rev.*, 1921, **17**, 7.

FIG. 2.



ionization tube was derived from an *AC* assembly kindly built for us by Mr. Sweeney of the General Mills Company.

The measurement of high vacuum by the ionization gauge is open to a variety of persuasive manipulations which makes it possible to obtain readings that are lower than the pressures in the apparatus to which the gauge is attached. After the tube has been baked and the electrodes bombarded, the clean surfaces absorb molecules of oil vapor for a considerable period and can reduce the pressure in the gauge temporarily to many times less than the equilibrium pressure which would be indicated later if the measurements were continued. In this paper, the conditions of measurement have been narrowly defined, but in order not to confuse the argument they are separated in a short Appendix.

THE TEST PUMP.

Accepting the description of butyl phthalate as a three-component liquid comprising the portions $(A - B) + (C \cdots Y) + Z$, it is seen that a three-compartment pump is required which shall afford small storage spaces for the $(A - B)$ and (Z) constituents and a larger space for the main bulk of liquid. This is provided conveniently, according to Figs. 3 and 4, by mounting two simple glass pumps in tandem. The most consistent results were obtained with the former, double

FIG. 3.

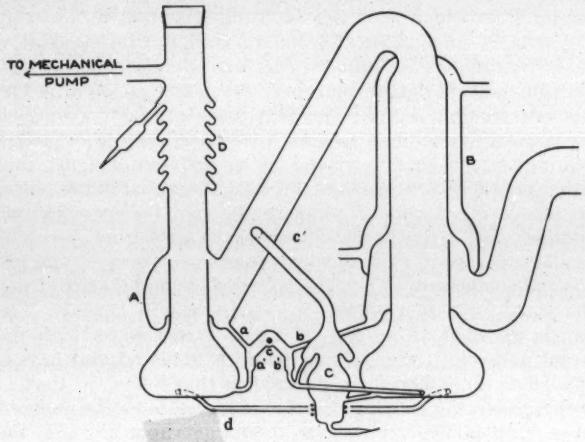
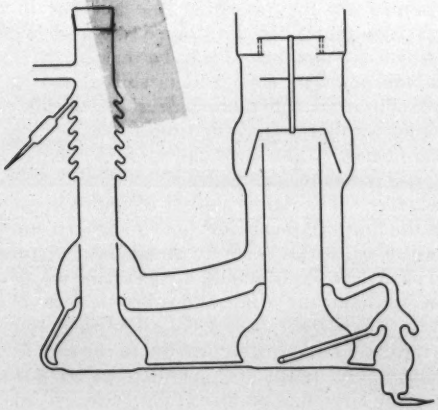


FIG. 4.



vertical type. In Fig. 3, *A* is the fore pump with a short receiving jet which need not be water-jacketed, terminating in a series of small re-entrant bulbs *D* designed to retain a few cubic centimeters of liquid. The fine pump *B* on the high vacuum side is larger and may be water-jacketed. The condensates from *A* and *B* travel by tubes *a* and *b* to a junction containing a steel ball (about 3/16″ diameter from a ball bearing) which can be moved by an external magnet into either pocket *a′* or *b′* or allowed to remain unused in the center depression *c*. A tube *d* connects the two boilers with one another; and a third tube allows oil to pass from *B* to the small evaporator *C* from which there are no exits except for gas (*c′*) and condensate (*f*). The boilers *A*, *B*, and *C* are warmed electrically and their upper portions are heavily lagged. The pumps are filled to a depth of 1/2 to 1 centimeter with the liquid under test, the backing pump is actuated and heat is applied to the boilers. In the records that follow, in Part II of this paper, the starting time is considered to be the moment when both pumps are seen to discharge vapor towards the receiving jets. It is apparent that the nonvolatile impurities will eventually accumulate in *C*, from which they may be drained occasionally.

The pumps are now assisting one another in series, *A* serving as fore pump for *B*. Three ways of working are possible which, for simplicity, may be termed:

Worst-tandem. The steel ball is shifted to the left and condensed oil from the fore pump passes into the fine pump and then back leftwards through the tube *d*.

Normal-tandem. The steel ball is in the center and each pump re-uses its own condensate.

Best-tandem. The ball is shifted to the right and condensate from the fine pump is boiled out in the fore pump returning rightwards to its own boiler by the tube *d*. Arranged thus, the butyl phthalate filling should be operating under optimum conditions, phthalic anhydride and other class *B* volatiles collecting in the rings *D*, the class *A* volatiles being rejected in the boiler *A*, the class *Z* impurities drifting to the sink *C*, while the substantially pure phthalate operates under low backing pressure in the large fine pump.

The practical question at issue is: Do the ultimate vacuums

differ for the three kinds of tandem setting? It will be shown that they do, profoundly.

The best-tandem figures in the data which follow are believed to be free from the defects itemized in the Appendix under "Criteria for Optimum Vacuum." The figures correspond, therefore, with the vapor pressures of the pure liquids at the prevailing room temperature.

VACUUM READINGS WITH THE THREE TANDEM SETTINGS.

The readings obtained for the worst-tandem setting varied with the sequence of testing. In order to secure the minimum difference between the three settings, the pump was operated first at best-tandem, then at normal-, and finally tested at worst-tandem. The oil was thus thoroughly degassed in the accepted sense. The three "tandem" values for butyl phthalate are:

TABLE I.

Oil Sequence.	At 25° C.		At 0° C.	
	Gauge Micro-amps.	P mm. Hg.	Gauge Micro-amps.	P mm. Hg.
Best-tandem	6	1.5×10^{-4}	.27	6.8×10^{-6}
Normal-tandem	15	3.8×10^{-4}	.45	1.1×10^{-5}
Worst-tandem	280	7.0×10^{-3}	10.00	2.5×10^{-4}

Altering the position of the steel ball has thus altered the pressure about forty times. Note that no other alteration has been made to the pump settings. With identical heat input, vacuum load and backing pressure, the ultimate vacuum in one case is forty times better than in the other; the factor responsible for the change is solely the changed internal path of the oil. The figures for normal-tandem seem, from the point of view of the theory advanced, disappointingly good, but in reality they have little meaning because they depend on the previous history of the oil. When the pumps are run first in worst-tandem, the normal-tandem reading is correspondingly higher.

The Apiezon oils benefit by the best-tandem sequence more than the phthalate, because the $(C \cdots Y)$ portion is a

graded mixture and the lower boiling members tend towards the fore pump while the more desirable phlegmatic parts operate in the fine pump. Table 2 records the data:

TABLE 2.

Kind of Oil.‡	Best-tandem.				Worst-tandem 25° C.	
	Micro amps.†		Pressure mm. Hg.		Micro-amps.*	Pressure mm. Hg.
	25° C.	Ice	25° C.	Ice		
Apiezon A, 1934 sample.....	3.00	.360	7.5×10^{-5}	9.0×10^{-6}	126.0	3.2×10^{-3}
Apiezon A, 1932 sample.....	.20	.040	5.0×10^{-6}	1.0×10^{-6}	16.0	4.0×10^{-4}
Apiezon B, 1934 sample.....	.02	.008	5.0×10^{-7}	2.0×10^{-7}	3.6	9.0×10^{-5}

* Figures are approximate.

† Figures are repeatable.

‡ Results obtained after 72 hours boiling in pumps.

If the foregoing figures are accepted, it becomes apparent how such disappointing vacuums are often encountered, for the performance of a conventional pump must surely be nearer the worst-tandem value than the best. They also show why the Apiezon oils alone have been able to yield the highest vacuums when employed with charcoal and phosphorous pentoxide traps. The worst-tandem limit for butyl phthalate at 25° C. is about 7×10^{-3} mm. and for Apiezon oil (*A* variety of 1932 and *B* of 1934) is 3×10^{-4} mm., and these are the pressures which would be obtainable immediately in an inverted type of pump. After continued boiling some of the volatiles would distill into the mechanical backing pump and the normal tandem limits might be neared, 3×10^{-4} and 5×10^{-5} for the two oils, respectively.

Charcoal and phosphorous pentoxide would improve the Apiezon vacuum enormously, allowing 10^{-7} mm. to be passed at room temperature. The less tenuous butyl phthalate, on the other hand, although improved by the charcoal, would be impaired by the pentoxide because the ester molecules are dehydrated by this reagent with the liberation of butylene and phthalic anhydride. P_2O_5 should never be used with the phthalate esters.

These admissions banish butyl phthalate from the high vacuum field under the conditions contemplated in this paper, that is, where a cooled trap cannot be employed. However, since the optimum vacuum is sensitive to small changes of trap temperature, the fluid becomes useful in those cases where a mildly refrigerated trap can be employed.

The following optimum vacuums, or pressures of residual butyl phthalate vapor, are available:

TABLE 3.

Pressure, Expressed in Millimeters Hg.	Trap Temperature 25° C.	0° C. (Ice)	− 18° C. (Ice and Salt)
P = pressures indicated by ionization gauge = vacuum level for physical purposes	1.5×10^{-4}	6.8×10^{-6}	3×10^{-7}
p = true pressure $= P\cdot\frac{\text{Mol. Wt. Air}}{\text{Mol. Wt. Phthalate}} = P/11$ = vacuum level for chemical purposes	1.4×10^{-5}	6.2×10^{-7}	2.7×10^{-9}

The pressure of residual vapor with Apiezon *A* in a three-compartment pump will be 5–10 times lower at corresponding temperature, depending on the sample of oil.

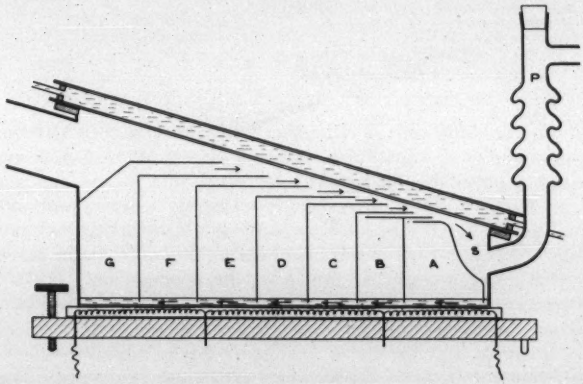
Below 0° C. the vapor pressures of many "pure" pump oils are less than 10^{-8} mm., but vacuums of this order are seldom obtained. Leakage and disengagement of gas from the walls of the vessel account for much of the spoilage but thermal decomposition of the pump oil can now become the limiting factor. The decomposition increases sharply with rise of temperature and the lower boiling pump fillings decompose less than the higher. Thus, butyl phthalate evolves less gas at its boiling point than hexyl phthalate does and Apiezon *A* boils with less decomposition than Apiezon *B*.

Where two pump fillings are available having residual pressures of 10^{-8} mm., one at 25° C. for example, and the other at − 10° C., the ultimate vacuum will be higher with the latter, provided the necessary trap containing ice and salt can be inserted. It is of advantage to use the lowest boiling pump filling which can meet the residual vapor pressure requirements at the temperature of the trap or baffle.

FRACTIONATION PUMP DESIGN.

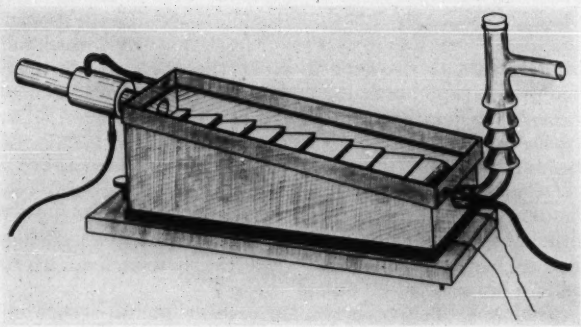
A three-compartment pump segregates the *A*, *B*, and *Z* impurities fairly well, but it cannot arrange in order the *C* ··· *Y* constituents of a mixed pump filling. A mixed pump filling can be put to great advantage in a multi-stage pump because the lower boiling fractions do most of the pumping at high pressure while the phlegmatic fractions simmer gently at the high vacuum end where they reduce the residual gas pressure to an exceedingly low value. In lieu of connecting many single pumps in tandem or attaching nozzles at points on a long distilling column, etc., etc., the desired effect can be secured by the simpler arrangement pictured in Figs. 5 and 6.

FIG. 5.



Here the container is a sheet metal box, rectangular in plan, wedge-shaped in elevation. Round the edge of the open top is brazed a stout steel flange, the upper surface of which is lapped to receive a sheet of plate glass. The glass forms the lower element of a transparent water-cooled cell. The inside of the box is filled with a number of bent partitions, the lower ends terminating a millimeter from the floor, the upper forming a series of jets, each a little wider than the one before. The box is mounted on an electric heater tapped in three

FIG. 6.



places so that extra heat can be applied to the incoming oil. The whole assembly rests on a table, which can be tilted by a leveling screw. The design illustrated is simple to construct, surprisingly difficult to render vacuum-tight. It is described here because it forms a model on which to hang certain arguments. A description of its more practical successor and the questions raised by its performance must be deferred to a later paper.

For the moment, consider the present pump filled with a mixture of equal parts of amyl- and β-phenyl ethyl phthalates,* to take an extreme case, and the heat input adjusted to maintain a uniform temperature of about 150° C. along the bottom of the pump during operation. Under vacuum, the amyl ester will begin to evaporate from the mixture and issue from the jets, condensing on the sloping glass ceiling down which it runs into the front of the pump and thence into compartment *A*. The contents of *A* are now richer in amyl phthalate and vigorous distillation ensues, giving strong pumping at the jet *a*. Distillation is going on to a lesser extent in *B*, so that the level of liquid falls, its place being taken by mixture from *A* which has lost some of its amyl phthalate. In the same way, *C* draws liquid from *B*, *D* from *C*, and so on till *F* and *G* receive

* See Part II of this paper.

liquid which is substantially free from amyl phthalate and is seven times purified from air and other volatile constituents. The mixed vapors from jet *D* should have reduced the pressure to below 10^{-5} mm. so that the β-phenyl ethyl ester, which fails to boil without decomposition in the three-compartment pump, can evaporate in the later compartments of this pump at a safe low temperature and provide a gentle stream of low pressure vapor through a short wide jet system to give the finishing touches to the vacuum. At the time of writing, the performance of this mixture cannot be verified because the possible vacuum of 10^{-10} mm. cannot be measured by the author's technique, but a butyl phthalate-heptyl phthalate mixture has been found to yield the best-tandem heptyl vacuum in this cascade pump.

An interesting property of a cascade pump is that unpurified fillings can be used. During the preparation of complex esters such as butyl benzyl phthalate, a mixture containing this substance with both the dibutyl and dibenzyl esters is produced from which it is difficult to separate the individuals. The mixture can be used as such in the cascade pump when the constituents soon take up their appropriate working positions.

The method of construction has another significance. Consider the conventional pumps in Fig. 1. A certain pump of the vertical type 1 was found to have a speed for air of three liters a second, while another pump of type 3 had a speed of ten liters a second. When these pumps were used to exhaust a system discharging condensible vapors instead of air, their relative speeds were reversed because only the vertical pump could reject the vapors. We may distinguish, therefore, between the *normal speed* and the *elimination speed* of a pump. Conditions which secure the highest performance for the one may greatly depress the other. The cascade pump has a relatively poor normal speed, for it is plain that if the many jets were used in parallel instead of series, the volume of air per units of heat input and oil used would be larger. The elimination speed, however, is excellent because not only does the condensate carry the dissolved vapors to the foot of the pump, but it discriminates between those it can re-use and those it should reject. The class *B* volatiles are passed into

the exit column *P*, but substances having volatilities equal to those of the mixtures in the forward compartments are put to work in these to do their quota of pumping. The affinity for an incoming vapor displayed by a pump filling ceases to be a disadvantage and confers an elimination speed which exceeds the pumping speed of the same jet system for air.

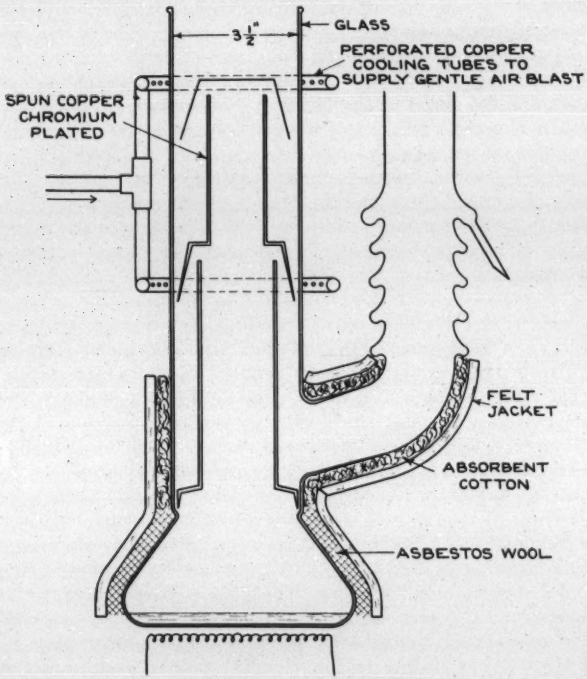
In chemical work, the elimination speed is of the first importance; in physical systems, the normal speed. Since, however, the two speeds become identical near the room vapor pressure of the pump filling (because the residual volatiles determine the optimum vacuum), it is necessary to adjust the pump to its best elimination speed when the highest vacuums are required.

ADAPTING CONVENTIONAL PUMPS.

Molecular distillation work rarely demands pressures lower than 3×10^{-4} mm. High elimination and high pumping speeds at this pressure can be secured in the simple single-stage unit shown as the fore pump in Figs. 3 and 4. The pump is run hot and the upper fractionating portion of the chimney is lagged with absorbent cotton. Benzyl phthalate is the preferred fluid and a backing pressure of less than 0.05 mm. should be provided. The efficiency is good with a jet diameter of two inches, the other dimensions being increased in proportion. Good normal speed with slightly decreased elimination is secured with *n*-amyl phthalate, the pump being cooled with a small air jet. The provision of a cold water jacket then becomes useful.

An inverted pump with fractionating features may be constructed according to Fig. 7. The points to note are: A short wide vapor supply, cooling restricted to the upper portions of the jacket, and an abnormally large side arm leading to the mechanical pump. The side arm is provided with catchment lobes and its junction with the main portion is heavily lagged. The heat input is adjusted until there is perceptible refluxing in the arm, but the outflow of vapor is not allowed to exert sufficient back pressure to interfere with the jet performance. Hexyl phthalate is about the heaviest ester suitable, but the Apiezon oils give good performance. The inverted pump could be improved further by providing an external boiler and jet for purifying the condensate and by

FIG. 7.



fitting a sink for the nonvolatile residues. This would merely result in a three-compartment pump and it would have been simpler to have constructed this at the start.

SUMMARY.

The vacuum obtainable with an oil diffusion pump is shown to be modified by impurities, some present in the original oils, some formed in the pump.

A pump having extra compartments to segregate the impurities is shown to yield higher vacuums than are usually

obtainable with a given liquid. The lowest vacuum at any temperature is a reproducible characteristic of the liquid.

Some pumping properties of butyl phthalate and the Apiezon oils are examined and the lowest pressures obtainable at 25° C. and 0° C. are recorded.

Various fractionation pumps are described which utilize the liquids under suitable conditions.

APPENDIX.

The vapors of pump oils are powerfully adsorbed to glass and metal surfaces, the degree of molecular crowding varying with every slight alteration of temperature. The walls of a 500 cc. flask in equilibrium with a butyl phthalate vacuum at 25° C. will evolve many thousands of volumes of gas on gentle warming. If the pressure is read immediately after cooling, it will be found to be less than that in the rest of the system owing to readsorption of the vapor by the walls. An ionization gauge that has been freshly torched and bombarded exerts a powerful "getter" action and may record a pressure a hundred times lower than that in the rest of the apparatus. It is possible that many of the exceedingly low pressures credited to oil vapor pumps, in the literature, have been secured in this manner.

The ultimate pressures recorded in this paper have been secured by approach from two directions: By watching the fall of pressure for some hours with the filament alight, but the gauge untorched, and watching the rise of pressure from the lowest reached after gentle torching with a Bunsen burner. If the two pressures did not eventually coincide the experiment was repeated. When the limiting pressure had been obtained, ice was placed in the trap between the pump and the gauge and it was ascertained that the pressure fell sharply, showing that the residual gas consisted chiefly of the vapor of the pump fluid. The pressure indicated before icing was thus determined by the vapor pressure of the pump filling at room temperature. It differed from the true vapor pressure according to the relation discovered by Dushman and Found.[14] The real pressure was about eleven times less than the indicated pressure, butyl phthalate containing eleven times more electrons per molecule than air.

In Tables I and II (above) the indicated pressures only have been given and it is felt that the degrees of vacuum reported in these papers have been presented on a conservative basis.

Criteria for Optimum Vacuum.

The "best possible" vacuum may be defined as that corresponding with the vapor pressure of the filling at trap or room temperature, whichever is the lower. When this point has been reached, it is found that the ionization gauge responds to the most trifling changes in this lowest temperature, cooling the trap from 25° C. to 0° C. reducing the reading of the ionization current nine or ten times. When ice immersion produces little or no improvement, or the degree of lowering is not repeatable from time to time, the vacuum is faulty and is being spoiled by one or more of the following factors:

(1) Leakage: Test—the oil manometer on the fore vacuum reads high and the reading will be lowered as vacuum grease is applied to the joints and doubtful glass seals. Immersing the trap in liquid air will scarcely improve the vacuum.

(2) Thermal Decomposition: Test—the reading of the oil manometer may be high and will increase with increase of heat input to the boilers. It will return to normal when heat is cut off entirely. Application of ice will be without effect, but immersing the trap in acetone and CO_2 and then in liquid air will yield progressive improvement as the thermal products are frozen out.

(3) The presence of class *B* volatiles—the oil manometer reads normally, the vacuum is not improved by ice, but solid CO_2 and acetone reduce it beyond measurable limits. Running with the fore pump *A* hot for a few hours reduces the untrapped vacuum to the theoretical best obtainable with the filling.

(4) The presence of a nearly similar constituent, such as ethyl phthalate, in a supposedly butyl phthalate filling. Test—the pressure is responsive to small temperature changes as though it were the limiting vacuum for the pump substance, but the reading is not low enough or accurately repeatable. The remedy is to lag the receiving jet of the fore pump until part of the oil has been distilled into the reservoir *R*. If this fails, the filling should be discarded.

The results recorded in the papers are believed to be free from defects (1), (3) and (4); and thermal decomposition (2) has not contributed sufficient gas to impair any but the highest vacuums, such as are rendered otherwise available by the use of a trap cooled with ice and salt.

High Pressure Oil Cable.—CHARLES E. BENNETT AND ROBERT J. WISEMAN of the Okonite-Callender Cable Co., Inc., describe, in *Electrical World*, Vol. 105, No. 25, a complete, new system of underground electrical transmission that is economical, simple and flexible. It is a simple cable system drawn into an oil-filled pipe line, the oil being kept under high pressure. The system is known as the Oilostatic transmission system. The pipe, roughly 50 per cent. larger in diameter than the circle circumscribing the assembled non-leaded, but insulated conductors, is filled with oil that is maintained at a pressure of 200 lb., per square inch. Before shipment it is tested for strength and soundness for factory welding, and the ends are sealed with special caps to prevent foreign matter from entering. The cable has the same thickness of insulation as is used in oil filled cables and covered with a thin lead sheath which is removed when the cable is drawn into the pipe. The oil storage and pressure equipment for short lines is placed at only one location. A hydro-vollifier is used when filling the pipe line with oil. The line is evacuated and the oil passes through the hydro-vollifier, which filters, dehydrates and degasifies the oil before it goes into the line. This transmission development offers large economies both in original construction and maintenance. It is feasible to use the system for underground transmission voltages well above the highest voltages now employed. Two installations of the Oilostatic transmission system exist at the present time. The first, an experimental installation operating at 66 kv., three phase, was made in 1932 at the Plymouth Meeting substation of the Philadelphia Electric Co. The second is an installation for single phase, 132 kv. operation constructed by the Penna. Railroad in connection with its electrification project at Baltimore, Md., and operating since January 1935.

R. H. O.

"There is a great need for interpreters and liaison officers as intermediates between the scientist and the layman. We must also bear in mind that a scientist is a layman in every sense but his own, and so he likewise needs to have the new things in other fields explained in non-technical language."—E. E. Slosson.

A METHOD OF DETERMINING THE OPERATING CHARACTERISTICS OF A POWER OSCILLATOR.

BY

E. L. CHAFFEE and C. N. KIMBALL,

Cruft Laboratory, Harvard University, Cambridge, Mass.

SUMMARY.

The performance of vacuum tube power oscillators is determined by tests made at 60 cycles. The low-frequency potentials are applied to the plate and grid electrodes from the 60-cycle power mains through suitable transformers. Wattmeters placed in the circuits indicate the magnitudes of the plate and grid power losses. The wave forms of and the phase angle between the alternating plate and grid voltages are determined from 60-cycle measurements. Radio-frequency measurements with the same tubes show close agreement with the results of the 60-cycle tests. A new method of presenting the results is also given in which the operating characteristics of the vacuum tube are shown as contours on the $e_p - e_g$ plane.

A vacuum tube operating as a power oscillator is a converting device which changes the direct-current power supplied by the plate-circuit power source into alternating-current power. The amount of power converted and the efficiency of conversion depend fundamentally upon the voltages applied to the vacuum tube. Hence, before the circuits for a power oscillator can be intelligently designed, complete knowledge of the operating characteristics of the converting tube as a function of the applied voltages is necessary.

The characteristics of the converting tube can be obtained from measurements made on the tube when operated under various conditions as a radio-frequency power oscillator, or by calculation from the static characteristic curves of the tube. The former method is laborious and is generally inaccurate. To the second method these comments apply with much greater force.

The following paper describes a simple and convenient method of determining the complete operating characteristics of a power tube. This method was suggested by the first author several years ago.

If the power oscillator is to operate at a frequency such that the time of flight of the electrons between the electrodes is negligible compared with the period of oscillation, the operation of the tube as a converter is independent of the frequency and dependent only upon the voltages applied to the tube. The operating characteristics of the tube can, therefore, be obtained at a low frequency where ordinary wattmeters, ammeters, and voltmeters can be used. The method to be described is carried out at 60 cycles.

As stated before the efficiency and power output of a triode power oscillator depends only upon the voltages impressed between cathode and grid, and between cathode and plate, and their phase relation, it being assumed that the cathode is heated to its rated value and that the emission is normal. Generally, in the normal use of a power oscillator the direct-current power is converted into power of a single frequency. Under this condition the plate circuit load is a tuned circuit and usually has such a low impedance at the harmonics of the fundamental frequency that the alternating component of the plate voltage is practically sinusoidal. The alternating component of the grid voltage also is generally sinusoidal although the degree of approximation to the sinusoidal form depends greatly upon the particular circuit used. The greatest efficiency results when these two alternating components are just opposite in phase.

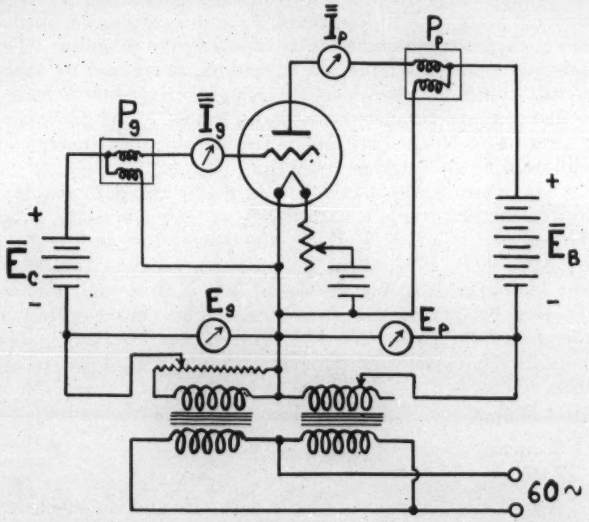
In the low-frequency method of testing, the usual tuned-circuit plate load is replaced by a transformer, the secondary terminals of which are connected to cathode and plate, and the primary winding of which is excited by the 60-cycle line. The sinusoidal plate voltage is consequently developed by the line instead of by the flow of plate current through an impedance. The impedance of the transformer from the secondary side, when the primary winding is connected to an "electrically stiff" line, is practically zero to the harmonics of 60 cycles. Consequently, the nonsinusoidal plate current flowing through the secondary coil of the transformer develops a negligible plate voltage corresponding to the harmonics. The impedance of the equivalent plate load which the transformer simulates is equal to the secondary voltage divided by the fundamental component of the plate current.

This equivalent impedance is, however, more easily determined as explained later.

Let $\bar{E}_B$ and $\bar{E}_C$ be the steady plate and grid voltages. Let E_p and E_g be the root-mean-square values of the sinusoidal components of plate and grid voltages, and let Φ be the phase angle between them. Further, let $\bar{I}_p$ and $\bar{I}_g$ denote the average values of the plate and grid currents. The tube loss, consisting of the sum of the plate power P_p and the grid power P_g, will be denoted by P_t.

The schematic diagram of connection for testing a power tube is shown in Fig. 1. The steady grid and plate voltages,

FIG. 1.



$\bar{E}_B$ and $\bar{E}_C$, are supplied by sources which have small impedances to the alternating currents. Storage batteries are convenient for low voltages. Generators or rectifiers shunted by large electrolytic condensers have been successfully used. The alternating components of the plate and grid voltages,

E_p and E_g, are supplied from the secondary coils of two separate transformers, the primary windings of which are supplied from the 60-cycle mains. The secondary winding of the plate transformer is tapped to enable the plate voltage to be varied.[1] The grid voltage is varied by a low-resistance potential divider connected across the secondary of the grid transformer. Two transformers are necessary in order to reduce coupling from the plate to the grid circuit which tends to cause self-oscillation. A single transformer to supply both voltages was first tried but self oscillation resulted so that this arrangement had to be abandoned for the two transformers.

The powers P_p and P_g dissipated at the plate and grid of the tube are given by the wattmeters shown in Fig. 1. The average plate and grid currents, $\bar{I}_p$ and $\bar{I}_g$ are given by two direct-current milliammeters as shown in the diagram. The 180-degree phase relation of E_p and E_g is secured by using tightly-coupled transformers, or by proper impedances placed in the primary circuits of the transformers. The direct and alternating voltages are given by suitable instruments as indicated in the diagram.

The instruments shown in Fig. 1 give the data required for calculating the characteristics of the converter tube. The power input $P_i = \bar{E}_B\bar{I}_p$; the power lost in the tube $P_t = P_p + P_g$ is obtained from the wattmeters; the power lost in the grid biasing resistance, which in actual practice replaces battery $\bar{E}_C$, is $P_c = \bar{E}_C\bar{I}_g$. The power output is therefore $P_0 = P_i - P_t - P_c$. The efficiency is P_0/P_i. The resistance in series with the grid circuit to supply the polarizing voltage is $R_c = \bar{E}_C/\bar{I}_g$. The resistance of the equivalent plate load is

$$(R_b)_\omega = \frac{E_p^2}{P_0}.$$

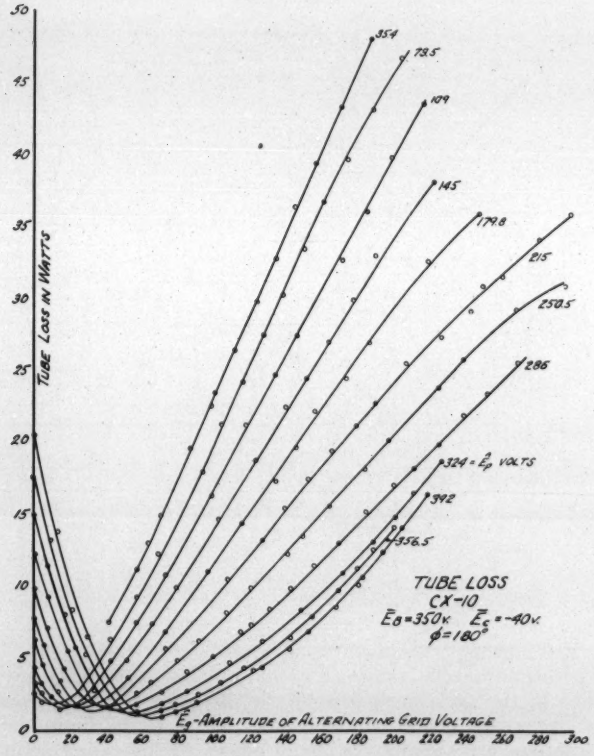
To obtain the manner in which P_0, P_t, and the efficiency vary with the four independent variables $\bar{E}_B$, E_p, $\bar{E}_C$ and E_g, any of the latter variables may be held constant and the others

[1] One of the transformers used in this research was a special transformer made and presented to the Cruft Laboratory by the General Electric Company. The authors wish to express their appreciation for the interest and assistance of the General Electric Company.

varied. For example, it is convenient to hold $\bar{E}_B$ and $\bar{E}_C$ constant through a given test and to obtain data by varying E_g for several constant values of E_p. Then the quantities P_0, P_t, and the efficiency may be plotted against E_g. One of such families of curves for P_t is shown for illustration in Fig. 2.

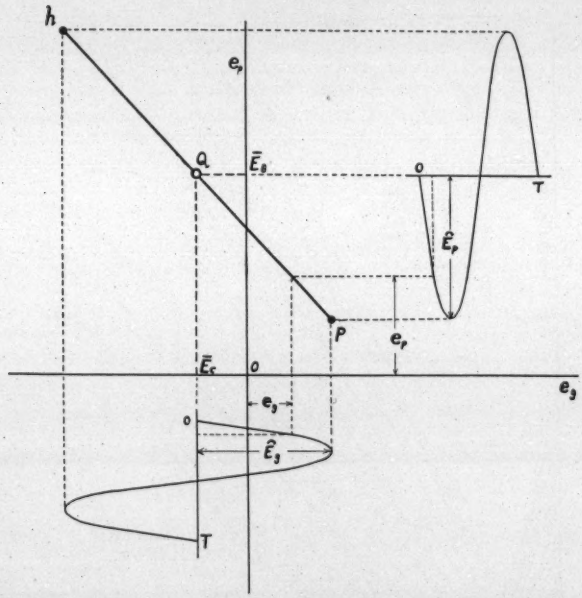
The results can, however, be presented in a much more

FIG. 2.



instructive manner by plotting contours of constant P_0, P_g, P_p, P_t, efficiency, $(R_b)_\omega$, and R_c on the coördinate plane for which the plate voltage and grid voltage are the coördinates. Referring to Fig. 3, values of instantaneous plate voltage e_p are plotted vertically and values of instantaneous grid voltage e_g are plotted horizontally. Point Q on this diagram, called the *quiescent point*, corresponds to the values of the steady plate and grid voltages. The alternating variations of plate and grid voltages are represented by the time plots in Fig. 3.

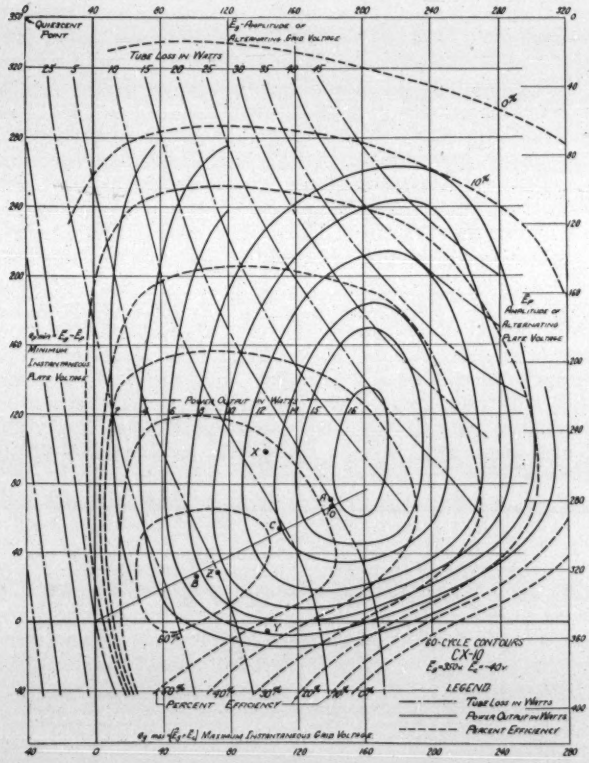
FIG. 3.



The instantaneous values of e_p and e_g corresponding to any time in the cycle are given by the distances from the axes to the proper points on these time plots. If the sinusoidal variations are 180 degrees out of phase, the operating point

determined by the instantaneous values e_p and e_g moves in a straight line hp, which is known as the *path of operation*. Point p represents the end of the path of operation corresponding to the half cycle when plate current flows. For every position of the end point p for a certain quiescent point there are corresponding values of $\hat{E}_p\hat{E}_g$, P_i, P_0, P_t, efficiency, R_c, and $(R_b)_\omega$. We can then plot the locus of positions of p

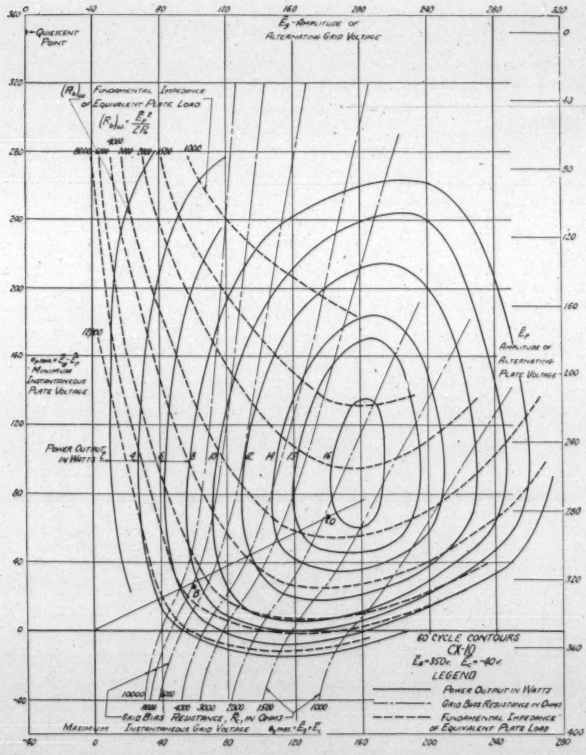
FIG. 4.



for which any one of the dependent variables has a constant value, thus giving contours of constant P_i, P_0, P_p, P_g, P_t, efficiency, R_c, and $(R_b)_\omega$. Data for plotting these contours are obtained from the families of curves for these dependent variables plotted against $\hat{E}_g$, one of which is shown in Fig. 2.

A contour diagram for a type 10 tube, giving P_0, P_t, and efficiency is shown in Fig. 4. Some of the contours of

FIG. 5.


Quiescent Point
E_g-Amplitude of Alternating Grid Voltage
Fundamental Impedance of Equivalent Plate Load
$(R_b)_\omega = \frac{E_p}{I_p}$
$e_{g\,min} = E_c - E_g$
Minimum Instantaneous Plate Voltage
E_p Amplitude of Alternating Plate Voltage
Power Output in Watts P_0
60 CYCLE CONTOURS
CK-10
E_b=350v. E_c=-40v.
LEGEND
Power Output in Watts
Grid Bias Resistance in Ohms
Fundamental Impedance of Equivalent Plate Load
Grid Bias Resistance, R_c, in Ohms
Maximum Instantaneous Grid Voltage $e_{g\,max} = E_g + E_c$

P_0 and efficiency are closed, the conditions for maximum P_0 being different from the conditions for maximum efficiency.

Figure 5 shows contours of $(R_b)_\omega$, R_c, and P_0 for the same conditions that held for Fig. 4. These two diagrams might have been combined except for the complexity of superimposing all contours.

Figure 6 gives contours for the same tube but for a plate voltage of 400 volts instead of 350 volts.

The method of using the contour diagram is illustrated by the following example. Suppose it be specified that the tube cannot operate safely with a tube loss P_t of more than 10 watts. If we are interested in obtaining the maximum power output corresponding to this tube loss, Fig. 4 shows that for this tube loss the maximum power output is a little over 14 watts and the efficiency is 57 per cent. The corresponding amplitudes of the alternating components of the plate and grid voltages are 296 and 152 volts, respectively. The point chosen is very close to point C on Fig. 4. Fig. 5 gives 2800 ohms for R_c and about 3400 ohms for the resonance resistance of the plate load. The circuits can easily be designed to give these voltages.

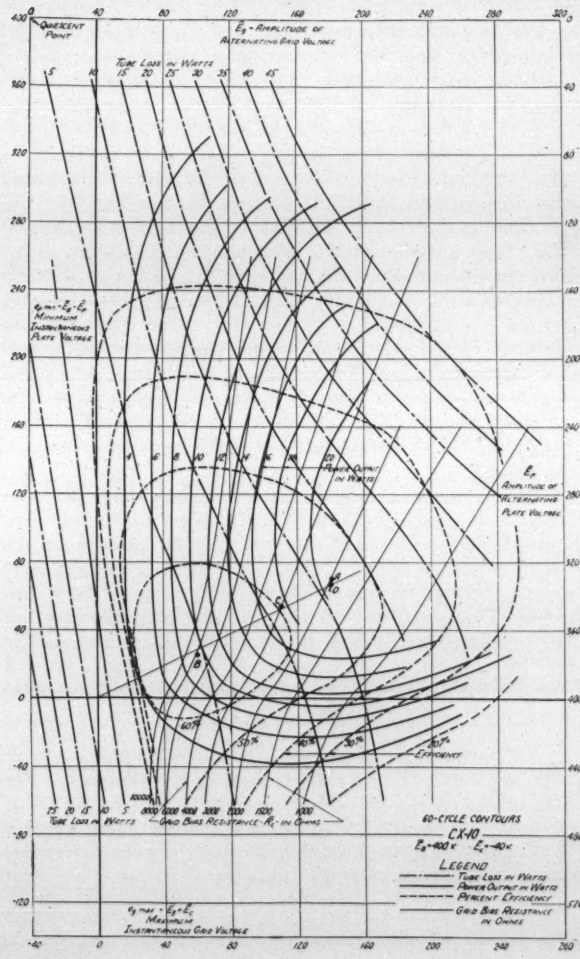
Referring again to Fig. 4, it is obvious that the most practical conditions of operation correspond to points along an approximately straight line AB which usually passes nearly through the origin. Along this line the greatest power output is obtained corresponding to any prescribed tube loss. Therefore for a practical test only the portion of the diagram in the neighborhood of this line need be determined. It is interesting to note that this line is a locus of constant ratio of

$$\frac{e_p \text{ minimum}}{e_g \text{ maximum}} = \frac{\bar{E}_B - \hat{E}_p}{\bar{E}_c + {}_g\hat{E}}.$$

For the type-10 tube this ratio is slightly less than 0.5. For some other types of tubes this ratio may be as great as 1.0 or even more. D. C. Prince[2] gives 1.25 as the value for this ratio as used in the calculation of the operating characteristics from the static characteristics.

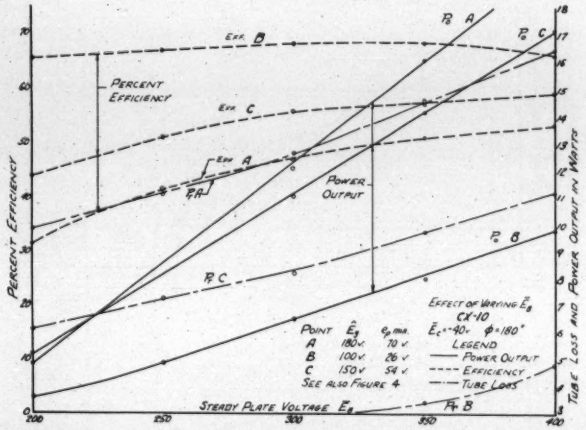
[2] D. C. Prince, *Proc. I.R.E.*, 11, pp. 275, 405, 527, June, August, October (1923).

FIG. 6.


QUIESCENT POINT
E_g - AMPLITUDE OF ALTERNATING GRID VOLTAGE
TUBE LOSS IN WATTS
$e_{g\,min} = E_g - E_c$ MINIMUM INSTANTANEOUS PLATE VOLTAGE
POWER OUTPUT IN WATTS
E_p AMPLITUDE OF ALTERNATING PLATE VOLTAGE
EFFICIENCY
TUBE LOSS IN WATTS — GRID BIAS RESISTANCE R_c - IN OHMS
$e_{g\,max} = E_g - E_c$ MAXIMUM INSTANTANEOUS GRID VOLTAGE
60-CYCLE CONTOURS
CX-10
E_b=400 v E_c=-40v
LEGEND
TUBE LOSS IN WATTS
POWER OUTPUT IN WATTS
PERCENT EFFICIENCY
GRID BIAS RESISTANCE IN OHMS

The curves of Fig. 7 show the manner in which P_0, P_1, and efficiency vary as $\overline{E}_B$ is varied for values of $\hat{E}_p$ and $\hat{E}_g$ corresponding to points A, B, and C of Fig. 4. Fig. 8 shows the variation of these quantities as $\overline{E}_C$ is varied instead of $\overline{E}_B$.

FIG. 7.



All of the discussion so far applies to the condition of phase opposition of the fundamental alternating components of the grid and plate voltages. This 180-degree-phase relation was secured by the tightly-coupled transformers which supplied the plate and grid voltages. The phase angle was measured and at no time did it vary more than a degree from 180 degrees.

In order to determine the effect of varying the phase angle, measurements were made when various amounts of ironless inductance were inserted in the primary circuit of the transformer which supplied the grid voltage. Fig. 9 shows the manner in which P_0, P_1, and efficiency vary with phase angle when the conditions corresponded to points X, Y, and Z of Fig. 4. The results show that in general a phase departure up to 10 from 180 degrees causes only slight variations in P_0,

FIG. 8.

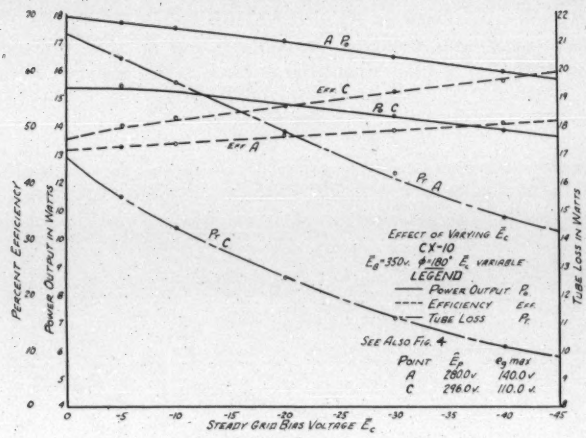
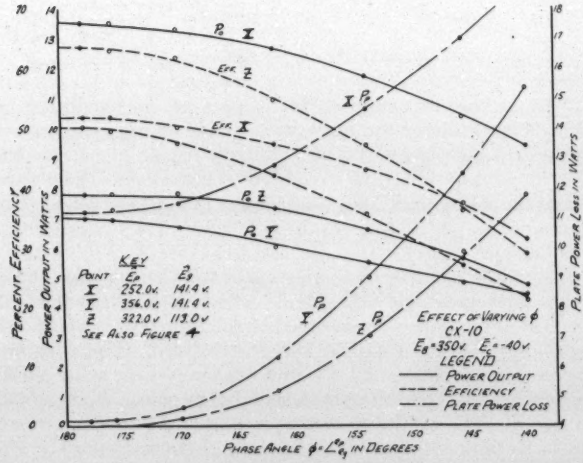

A P_p
EFF. C
P_p C
EFF. A
P_p A
P_p C
EFFECT OF VARYING E_c
CX-10
E_b=350 v. φ=180° E_c VARIABLE
LEGEND
POWER OUTPUT P_p
EFFICIENCY EFF.
TUBE LOSS P_t
SEE ALSO FIG. 4
POINT E_p e_g MAX
A 280.0 v. 140.0 v.
C 296.0 v. 110.0 v.
PERCENT EFFICIENCY
POWER OUTPUT IN WATTS
TUBE LOSS IN WATTS
STEADY GRID BIAS VOLTAGE E_c

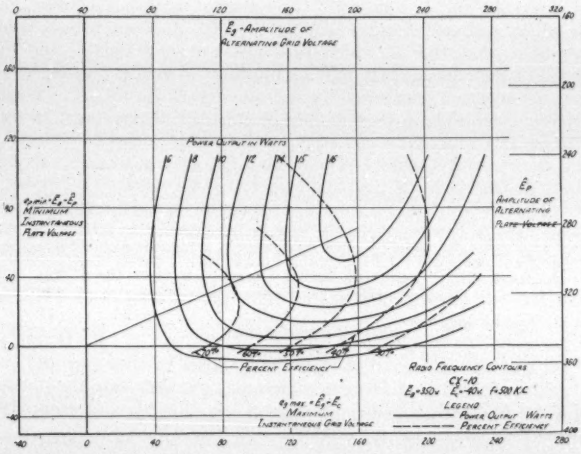
FIG. 9.


P_p I
EFF. Z
I P_p
EFF. I
P_p Z
P_p Y
KEY
POINT E_p E_g
I 252.0 v. 141.4 v.
Y 356.0 v. 191.4 v.
Z 322.0 v. 113.0 v.
SEE ALSO FIGURE 4
Y P_p
Z P_p
EFFECT OF VARYING φ
CX-10
E_b=350 v. E_c=-40 v.
LEGEND
POWER OUTPUT
EFFICIENCY
PLATE POWER LOSS
PERCENT EFFICIENCY
POWER OUTPUT IN WATTS
PLATE POWER LOSS IN WATTS
PHASE ANGLE φ=L.e_g IN DEGREES

P_t, and efficiency. The variation of efficiency is greatest for point Z which corresponds to the highest efficiency obtainable at the particular values of steady plate and grid voltages.

The same tube, type 10, used in obtaining the curves of Fig. 4 was also tested at a frequency of 500 kilocycles. The

FIG. 10.


E_g = Amplitude of Alternating Grid Voltage
Power Output in Watts
E_p = Amplitude of Alternating Plate Voltage
$e_{g\,min} = E_g - E_c$ Maximum Instantaneous Plate Voltage
$e_{g\,max} = E_g - E_c$ Maximum Instantaneous Grid Voltage
Percent Efficiency
Radio Frequency Contours
CX-10
E_b=350 E_c=-40 f=500 K.C.
Legend
Power Output Watts
Percent Efficiency

results shown in Fig. 10 check the measurements obtained by the low-frequency method very closely, the average deviation being only a few per cent. which is mostly due to experimental errors.

The low-frequency method of testing power tubes just described has also been applied to determine the operating characteristics of tubes used in other ways, for example, as power amplifiers, modulators, etc. The contour method of presenting the results seems to have the advantage of conveying in condensed form a great deal of information concerning the tube. It is hoped that tube manufacturers may sometime adopt this or some equivalent scheme of presenting the operating characteristics of their power tubes.

The "Biway" System of Electric Platforms for Mass Transit.—NORMAN W. STORER, in *Electrical Engineering*, Vol. 54, No. 12, reviews various schemes of moving sidewalks and platforms dating from 1874, for the solution of an adequate means of transportation of people in congested business districts in large cities. Claiming that if the cities of the future are to be made up of skyscrapers, the author points out that the present methods must be changed radically. The "biway" is the latest consideration for the solution of the problem. It consists of two adjacent moving platforms, one of which operates continuously at a speed of about fifteen miles per hour, the other of which varies between a standstill and the speed of the continuously moving platform to enable passengers to transfer between the stationary and moving platforms. The biway offers convenience in that it may be boarded at any point on the system and will give a non-stop ride to within a short distance of the destination, greater speed than existing transit methods for short distances, seating capacity up to 60,000 passengers per hour past a given point, and economy of operation by the use of regeneration. The biway possesses the attribute of safety to a high degree. The cost of the system is dependent on local conditions. Estimates made from actual costs of subways indicate that the biway will cost less to construct and install than the subways and will give much better service.

R. H. O.

"Translators are like busy match-makers: they sing the praises of some half-veiled beauty, and extol her charms, and arouse an irresistible longing for the original."—Goethe.

MEASUREMENT OF ABSOLUTE VISCOSITY BY THE FALLING SPHERE METHOD.*

BY

LESLIE R. BACON, Ph.D.,

Philadelphia Quartz Co., Philadelphia, Pa.

ABSTRACT.

The Stokes formula for calculation of viscosity of a fluid fails badly when applied over the range 10 to 10,000 poises under ordinary conditions. Many viscosity data based on this relation which is valid only for a medium infinite in extent appear seriously in error. Several published corrections also fail but the Faxen relation, based on strict hydrodynamic theory, gives results in good agreement with values obtained by the improved capillary tube technique. Viscosity measurements on glycerol and "Viscous Oil" by the falling sphere method agree with values reported by Armour & Co., and by the Bureau of Standards over the range 7 to 3660 poises with maximum differences of less than 1%.

Considerable practical as well as scientific interest attaches to the findings above since the requirements of apparatus and technique for measurement of absolute viscosities over a wide range with high accuracy are simple, inexpensive and generally available. The method is especially well suited for the range 10 poises and upwards and has been used in commercial research.

INTRODUCTION.

The motions of bodies through fluid media concern each of us constantly but the laws of such motions are of the utmost complexity. These motions may be of the most trivial importance or of the utmost gravity, trivial perhaps in the settling of sugar in our iced tea, less so when we have to deal with the rates of sedimentation of suspended matter in our public water supplies and of ultimate concern in the forces attending flight of an airplane. Lubrication in many aspects is a special case of motion of a body in fluid medium.[1]

The laws of such motions are still imperfectly understood, even for simple bodies. One property of the fluid medium alone appears to be common and vital to the consideration of motion of a body therein, namely viscosity or fluidity, its mathematical reciprocal.

Viscosity, mathematically definable in terms of units of force, distance and velocity, lends itself to measurement by

* Presented at the Annual Meeting of the Society of Rheology, New York City, October 12, 1935.

mechanical devices of limitless variety. Most of these are not useful for the direct measurement of absolute viscosity on account of non-calculable frictional losses however small, unless calibrated against fluids of known viscosity.

Two mathematically exact methods are available which do not require the use of standardizing liquids. The first is the capillary tube method, formulated by Hagen, developed by Poiseuille, Bingham and others, and long since accepted as the reference method of measurement. The second is the method of the falling sphere, the laws of which were first formulated by Stokes,[2] improved on by Ladenburg,[3] Oseen [4] and others, and only recently brought to mathematical perfection by Faxen.[5, 6] The importance of Faxen's work has been overlooked almost completely except for Barr's Monograph on Viscometry [7] and the papers of Liebster [8] and Schmiedel.[9] These papers have been directed more particularly to the experimental verification of the forces acting than to the development of a useful technique.

THEORY OF THE FALLING SPHERE METHOD.

The viscosity range over which falling sphere principles have been applied extends at least from 10^{-4} to 10^{12} poises, or we may say, from gases to glasses. Our own work falls in the range 10 to 10^4 poises which chances to have been investigated relatively little.

The most satisfactory résumé of the theory of the falling sphere method in English is given by Barr.[7] Older and less extended discussions appear in Hatschek's [10] and Bingham's [11] works. A very recent volume of interest to those mathematically inclined is by Tietjens.[12]

The basic principle underlying the falling sphere method of viscosity measurement may be stated thus:

"If a body is acted upon by a constant force and the resistance to its motion is proportional to the velocity or to any power of the velocity, the body will eventually attain a constant or terminal velocity such that the resistance experienced is equal and opposite to the driving force."

Stokes by neglecting the so-called semi-quadratic inertia terms of the form

$$\rho u \frac{\partial u}{\partial x}$$

of the general hydrodynamic differential equations arrived at the solution

$$W = 6\pi\eta rv, \tag{1}$$

which when equated against the driving force $4/3\pi r^3(\sigma - \rho)g$ yields the result commonly referred to as Stokes' law:

$$\eta = 2/9\ gr^2(\sigma - \rho)/v. \tag{2}$$

In the above expressions

W = resistance to motion of sphere moving with uniform velocity v,
η = viscosity of the fluid,
r = radius of the sphere,
σ = density of the sphere,
ρ = density of the fluid medium,
g = acceleration due to gravity.

The above relation is a first order approximation only, warranted only when the so-called Reynolds number

$$R = \frac{2rv\rho}{\eta} = \frac{dv\rho}{\eta}$$

be negligible compared to unity, i.e. $dv\rho/\eta \ll 1$. This function expresses a relation between inertia and viscosity forces and is a mathematical formulation of assumption (a) in the following group involved in the formulation of Stokes law:

(*a*) The motion of the sphere relative to the fluid is slow.
(*b*) The fluid is infinite in extent.
(*c*) The fluid is homogeneous.
(*d*) The sphere is rigid.
(*e*) The motion is steady and free from accelerations.
(*f*) There is no slip between fluid and sphere, i.e., the fluid film in contact with the sphere moves with the same velocity and direction.

Ordinarily with the use of solid spheres assumptions (*c*), (*d*) and (*e*) are perfectly fulfilled. It is the conclusion of Bingham that slip does not occur when the fluid wets the solid and of Bulkley [13] that the influence of the solid wall

upon viscous flow (capillary tube technique) cannot extend to more than .02 or .03 micron if it exists at all.

We are concerned only with assumption (*b*) in this paper. The problem of the influence of the proximity of a solid wall on motion of bodies in fluids has engendered a few theoretical corrections and several empirical ones. Ladenburg [3] proposed the relation

$$W = 6\pi\eta rv(1 + 2.4r/R), \tag{3}$$

which leads to the expression

$$\eta = \frac{2gr^2(\sigma - \rho)}{9v(1 + 2.4d/D)}, \tag{4}$$

where d = diameter of sphere of radius r,
D = diameter of cylindrical tube of radius R,
v = velocity of the sphere relative to wall of tube.
This was arrived at on the assumption of the sphere moving axially and vertically in a tube of infinite length.

More recently Faxen has carried the solution of Oseen's equations to completion, arriving at a function which may take the form

$$W = 3\pi d\eta v \Big/ \left[1 - \frac{3R}{16} - \frac{d}{D}f(R\,D/d) + 2.09(d/D)^3 - 0.95(d/D)^5\right]. \tag{5}$$

This has been derived on the assumption that the terms R^2, $R(d/D)^2$ and $(d/D)^6$ are negligible compared to unity. When R^2D/d also is negligible (5) simplifies to

$$W = 3\pi d\eta v/[1 - 2.104(d/D) + 2.09(d/D)^3 - 0.95(d/D)^5]. \tag{6}$$

Equating this resistance against the driving force, we come out to

$$\eta_F = \frac{2}{9}\frac{gr^2(\sigma - \rho)}{v}[1 - 2.104(d/D) + 2.09(d/D)^3 - 0.95(d/D)^5], \tag{7}$$

where η_F is the viscosity calculated from this equation. This may be written

$$\eta_F = \eta_S F, \tag{8}$$

where η_S = the viscosity calculated by Stokes' formula (2) and F is a factor determined by the function of (d/D) indicated.

Ladenburg,[3] Sheppard [14] and Schmiedel [9] have published data on end effects caused by boundaries at the surface and at the bottom of the vessel. The results are generally unsatisfactory and if time measurements are confined to the region of constant velocity it is better to neglect end corrections altogether. That is the case with the data to be reported.

EXPERIMENTAL.

A. Ball Bearings.

Stainless steel ball bearings 5/16, 1/4, 3/16 and 1/8 inches in diameter and carbon steel ball bearings 1/16 and 3/64 inches in diameter were secured from a large manufacturer. Uniformity of weight was tested at random with the results given in Table 1. The 1/16 inch balls may have been less

TABLE 1.

Weights of Individual Representative Balls.

d.	5/16".	1/4".	3/16".	1/8".
1..	2.0189 g.	1.0355 g.	.4318 g.	.1289 g.
2..	206	55	311	89
3..	206	57	316	89
4..	192	56	315	90
5..	189	43	315	89
6..	189	54	315	91
7..	190	56	286	90
8..	264	48	317	89
9..	192	55	316	90
10..	207	55	319	89
Ave..	2.0202	1.0353	.4313	.1290

uniform judging from the following figures:

No. of Balls Weighed.....	496	532	376	100	901	1001
Average Weight, mg.....	16.32	16.39	16.40	16.35	16.36	16.35

No comparative data were taken on the 3/64″ balls. The above averages may not represent the maximum variations.

If we assume accurate dimensions of the balls the errors indicated in Table 2 may follow. If on the other hand we

TABLE 2.

Maximum Variations in Calculated Viscosity Attributable to Variations in Balls.

d.	Assuming Accuracy of Dimensions (Variations in Density).	Assuming Accuracy of Density (Variation in Dimensions).		
		Stokes.	Ladenburg.	Faxen.
5/16...	.38%	.12%	.17%	.25%
1/4....	.14	—	—	—
3/16...	.77	.26	.34	.41
1/8....	.16	—	—	—
1/16...	.49	.17	—	—

assume constant density for balls of a given size it follows that inaccuracies in diameter may be many times the presumed 0.0001″ tolerance. The corresponding errors on this assumption are also indicated.

Specific gravity of the balls was determined at 20° C./20° C. using pycknometers. An accuracy of 0.001 is sufficient using steel balls. The data appear in Table 3.

TABLE 3.

Specific Gravity (20° C./20° C.) of Ball Bearings.

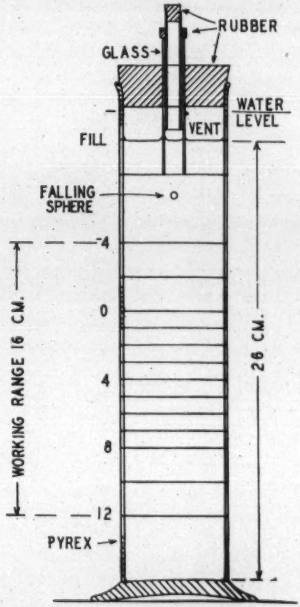
	5/16″.	1/4″.	3/16″.	1/8″.	1/16″.	1/16″.	3/64″.
No. Balls Used.....	4	8	8	50	300	300	500
Sp. Gr.....	7.730	7.729	7.648	7.711	7.764	7.810	7.751
Sp. Gr. Calc. from Ave. Wt., Assuming Exact Dimensions.....	7.715	7.722	7.626	7.698	7.807		7.805
Value Used.....	7.723	7.726	7.637	7.705	7.814*		7.778

* Independent determination by another method gave 7.867. Ave. of four values, 7.814.

B. Tubes.

Special footed Pyrex tubes of various diameters were made up based on recommendations from the literature [7, 15] and our early experience as shown in Fig. 1. Dimensional data are

FIG. 1.



Tubes used for measurement of viscosity.

given in Table 4. These cylinders were found to show variations in diameter at different heights, and eccentricity.* The average internal diameter of two parts of the range in which velocity measurements were taken are shown in the table and the average taken for calculations.

The maximum differences in diameters at the same height obtained by caliper measurements were .02 cm. for Tube B_2, .07 cm. for C_2, .06 cm. for D_2, .05 cm. for E_1, .18 cm. for F_1 and .13 cm. for F_2. It appears probable that balls falling in

* It is now understood that Fish-Schurman Corp., New York City, offers "Jena KPG Precision Bore Tubing" accurate to 0.001 cm. in uniformity of internal diameter, or even 0.0001 cm. for short lengths.

TABLE 4.

Tube Data.

Tube.	G. Water Between Rings.		I. D. Calculated.			Per Cent. Difference in I. D. Values.
	4 to 12.	− 4 to 4.	4 to 12.	− 4 to 4.	Ave.	
A_1...	39.1	39.2	2.498 cm.	2.501 cm.	2.500 cm.	.12
A_2...	39.6	39.7	2.514	2.517	2.516	.12
B_1...	74.0	74.6	3.438	3.444	3.441	.17
B_2...	76.4	75.7	3.492	3.476	3.484	.46
C_1...	128.5	123.3	4.520	4.422	4.471	2.26
	129.2	123.0	4.522	4.418		
C_2...	127.2	122.2	4.488	4.404	4.448	1.84
	127.3	122.5	4.490	4.410		
D_2...	211.1	203.8	5.790	5.684	5.739	1.79
	211.1	204.4	5.790	5.690		
E_1...	270.0	270.4	6.550	6.558	6.554	.12
F_1...	390.5	389.0	7.882	7.866	7.874	.20
F_2...	387.4	372.4	7.843	7.689	7.766	1.98

cylinders of elliptical cross section will experience greater resistance than when falling in a truly circular cylinder of the same cross section. This difference has not been evaluated but is believed safely within the 1 per cent. precision originally sought in our work.

The effect of inaccuracy in measurement of tube diameter on viscosities calculated by the Ladenburg or Faxen relations may be evaluated for balls of any given size. It is possible to deduce limits of error in D or d/D consistent with the attainment of any prescribed precision of viscosity measurement. Taking the percentage differences in D values for the two sections of the tubes as given in Table 4, it has been determined that to assure a precision of 0.5 per cent. in viscosity the sizes of balls must be limited as follows:

Tubes A_1, A_2, B_1, B_2, E_1, F_1: Balls 5/16″ or larger permitted.
Tube F_2: Limited to balls 1/4″ or smaller.
Tubes C_2, D_2: Limited to balls 3/16″ or smaller.
Tube C_1: Limited to balls 1/8″ or smaller.

C. Technique of Viscosity Measurements.

Viscosity measurements are made as follows (see Fig. 1): After bubbles have been eliminated and constant temperature reached in the thermostat, a ball is introduced through the

guide tube. The outer guide for balls up to 5/16″ is conveniently 0.9 cm. in diameter. This dips 2 cm. below the liquid surface and carries a vent for air pressure equalization. A second opening slightly below the surface may be desirable in some cases. For small balls one or more removable inner guides should be added; these do not dip below the surface. Axial travel of the ball is automatically assured. These guide tubes slow the ball down, permitting it to reach thermal equilibrium with the liquid and to dissipate the kinetic energy acquired through falling while still outside the measuring range. The slow rate of travel through the liquid in the guide provides time for the complete wetting of the surface and detachment of air bubbles, a most important function which can hardly be realized in any other way. The success of the whole operation is largely dependent, when using small apparatus, on the proper relations being maintained between guide tube, depth of immersion, centering and ball size.

A ball in traveling through the guide tube draws the liquid level downward. If through shallow immersion a bubble is drawn out of the tube, it will follow the ball and may be carried down several centimeters or even to the bottom by succeeding balls, always exerting forces disturbing to the normal travel. When the ball drops from the tube it accelerates. The design should be such as to permit attainment of constant velocity before timing begins, which requires the liquid level within this interval to come back to the "Fill" level within the guide tube. Four centimeters of free fall is the minimum safely allowable for good work; six or eight would be better.

In our work timing was regularly done for the intervals (− 4 to 0), (0 to 8), and (8 to 12), demonstrating, within the limits of other possible errors, that constant velocities were maintained throughout the 16 cm. interval which was ordinarily used for calculation of viscosity. Timing was done using stop watches reading to 1/5 sec., properly regulated. Measurements were not made while two balls were falling simultaneously or while air bubbles of appreciable size were present. Tubes were not moved while balls were falling, and special pains were taken to insure vertical alignment of the axis. The course of the bearings was viewed against a

lighted background through the glass wall of the thermostat. Since the rings extended fully around the tubes and the travel was relatively slow, accurate timing was insured.

For highly viscous substances the matter of dependable temperature control is of highest importance. The temperature coefficient of viscosity for some of our materials was upwards of 30 per cent. per degree C. Our thermostat functioned to 20 ± 0.03 per cent. C. It is very necessary to have the level of the liquid under measurement well below the level of the thermostat. The measuring interval should not begin at a distance below the surface less than the diameter of the tube.

COMPARISON OF VISCOSITY FORMULAS.

A. Data.

For two extended series of observations at different high viscosity ranges, special heavy grades of silicate of soda solutions were secured. These were specially treated to secure homogeneity in the fullest measure. Small air bubbles could be separated after closing the viscosity tubes by warming the tube in water not quite up to the silicate level, therefore avoiding surface evaporation, condensation and filming.

These solutions, designated Silicates A and B, showed specific gravities at 20° C./20° C. of 1.724 and 1.701 respectively. A series of 30 viscosity measurements was made for each silicate representing all combinations between balls of five diameters and tubes of six diameters, such that the d/D range explored was from .0202 to .3175. These results are set forth in Tables 5 and 6.

B. End Effects.

We cannot deduce anything conclusive from inspection of the tables relative to end effects. The Table 5 values are more significant than Table 6 results for comparing times to fall through specified distances. For small tubes, A, B, C, and perhaps D, the velocity over the first 4 cm. appears slightly higher than for the middle or final intervals, which run more or less equal. For Tube E, velocities are slightly higher in the final interval, and lowest in the first 4 cm. Since the results are not consistent with change of ball size for a given tube and may or may not accord with tube irregularities of Table 4 it is concluded that other influences have obscured any real effects.

TABLE 5.

Effect of Experimental Conditions on Viscosity. Silicate A.

Ball d, cm.	d/D.	Sec. to Fall.				Viscosity Calculated by Various Formulæ.				
		4 cm. (− 4–0).	8 cm. (0–8).	4 cm. (8–12).	16 cm.* (− 4–12).	η_S.	η_L.	η_B.	F.	η_F.
Tube A_2 : D = 2.516 cm.										
.1588	.0631	2540	5005	2647	10,192	5,309	4611	4573	.8677	4607[z]
.3175	.1262	381[a]	1530	757	2,668[g]	6,224	4777	4641	.7387	4598
.4762	.1893	404	821	408	1,633	7,431	5110	4824	.6156	4575
.6350	.2524	274	555	276	1,105	9,075	5651	5160	.5016	4552
.7938	.3155	222	450	224	896	11,492	6540	5757	.3988	4583
									Ave.	4583
Tube B_2 : D = 3.484 cm.										
.1588	.0456	2428	2447[e]	2445[g]	7320[h]	5083	4582	4561	.9042	4596[z]
.3175	.0911	677	1375	698	2750	5626	4617	4543	.8098	4556
.4762	.1367	345	697	350	1392	6335	4770	4614	.7176	4546
.6350	.1823	273[b]	385[d]	221	879	7219	5022	4758	.6289	4540
.7938	.2278	160	325	162	647	8298	5365	4965	.6447	4520
									Ave.	4552
Tube C_2 : D = 4.448 cm.										
.1588	.0357	2370	2380[c]	2391[g]	7141[h]	4959	4568		.9250	4587
.3175	.0714	648	1305	652	2605	5330	4550		.8506	4534
.4762	.1071	316	640	321	1277	5811	4623		.7772	4516
.6350	.1428	193	391	197	781	6414	4777		.7055	4525
.7938	.1785	136	277	141	554	7106	4975		.6361	4520
									Ave.	4536
Tube D_2 : D = 5.739 cm.										
.1588	.0277	2323	2320[c]	2305[g]	6948[h]	4825	4524		.9417	4544
.3175	.0553	622	1260	625	2507	5129	4528		.8839	4534
.4762	.0830	147[a]	604	298	1049[g]	5456	4550		.8266	4510
.6350	.1106	175	536[f]	—	711	5839	4615		.7701	4497
.7938	.1383	117	244	125	486	6233	4680		.7145	4453[z]
									Ave.	4508
Tube E_1 : D = 6.554 cm.										
.1588	.0242	2355	2295[c]	2330[g]	6980[h]	4847	4581		.9491	4600
.3175	.0484	625	1235	615	2475	5064	4537		.8984	4549
.4762	.0727	293	591	289	1173	5338	4545		.8478	4526
.6350	.0968	175	347	173	695	5708	4632		.7982	4556
.7938	.1211	120	237	118	475	6092	4720		.7489	4562
									Ave.	4559

TABLE 5.—*Continued.*

Ball *d*, cm.	*d*/*D*.	Sec. to Fall. 4 cm. (− 4–0).	8 cm. (0–8).	4 cm. (8–12).	16 cm.* (− 4–12).	Viscosity Calculated by Various Formulæ. η_S.	η_L.	η_B.	*F*.	η_F.
				Tube F_2 : D = 7.766 *cm.*						
.1588	.0204	2348	4564	2292	9204	4782	4559	4555	.9571	4577
.3175	.0409	613	1211	609	2433	4966	4522	4505	.9140	4539
.4762	.0613	282	571	286	1139	5170	4507	4472	.8715	4506
.6350	.0818	163.5	328	167	658.5	5396	4511	4451	.8290	4474
.7938	.1022	111	224	112	447	5719	4592	4502	.7872	4512
									Ave.	4520
									Ave. All Tubes	4543

[a] 2 cm. fall. [d] 7 cm. fall. [g] 14 cm. [z] Highest value.
[b] 5 cm. fall. [e] 4 cm. fall. [h] 12 cm. [z'] Lowest value.
[c] 4 cm. fall. [f] 12 cm. fall. * 16.04 cm. for F_2.

TABLE 6.

Effect of Experimental Conditions on Viscosity. Silicate B.

Ball *d*, cm.	*d*/*D*.	Sec. to Fall. 4 cm. (− 4–0).	8 cm. (0–8).	4 cm. (8–12).	16 cm.* (− 4–12).	Viscosity Calculated by Various Formulæ. η_S.	η_L.	η_B.	*F*.	η_F.
				Tube A_1 : D = 2.500 *cm.*						
.1588	.0635	268	543	266	1077	563.0	488.5	484.5	.8669	488.1
.3175	.1270	79.5	161	80	320.5	658.2	504.4	489.9	.7371	485.2
.4762	.1905	42.5	87	42	171.5	783.5	537.7	507.3	.6133	480.5
.6350	.2540	29	58.5	29.3	116.8	962.9	598.2	545.7	.4988	480.3
.7938	.3175	22.5	47.5	24	94.0	1210.3	686.9	604.0	.3958	479.0
									Ave.	482.6
				Tube B_2 : D = 3.484 *cm.*						
.1588	.0456	257	517	260	1034	540.6	487.3	485.1	.9042	488.8
.3175	.0911	72	146	78	296	607.9	498.9	490.8	.8098	492.3
.4762	.1367	37	73.5	37.5	148	676.1	509.1	492.4	.7176	485.2
.6350	.1823	23	46	24	93	766.7	533.4	505.2	.6289	482.2
.7938	.2278	17.5	34.5	17.5	69.5	894.8	578.5	535.4	.5447	487.4
		17	35	17	69	888.4	574.4	531.6	.5447	483.9
									Ave.	486.6

TABLE 6.—*Continued.*

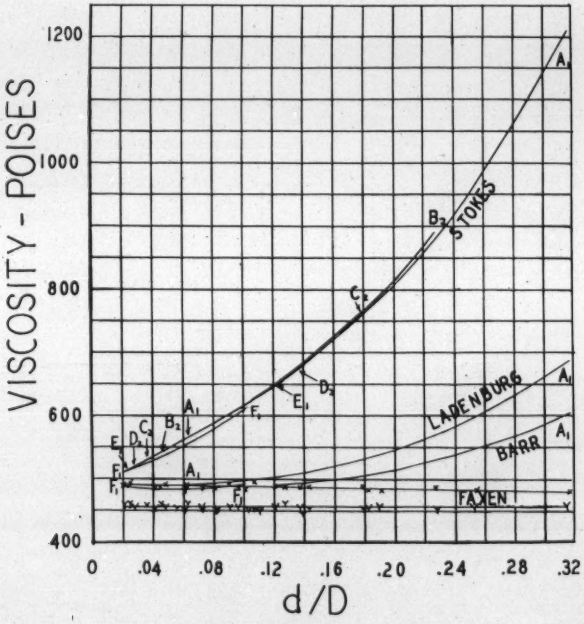
Ball d, cm.	d/D.	Sec. to Fall.				Viscosity Calculated by Various Formulæ.				
		4 cm. (− 4–0).	8 cm. (0–8).	4 cm. (8–12).	16 cm.* (−4–12).	η_S.	η_L.	η_B.	F.	η_F.
Tube C_2 : D = 4.448 cm.										
.1588	.0357	253	508	256	1017	531.7	489.7		.9250	491.8
.3175	.0714	70	140	70	280	575.1	491.0		.8506	489.2
.4762	.1071	34.5	69.5	35.5	139.5	637.3	507.0		.7772	495.3[z]
.6350	.1428	20.5	42	21	83.5	688.4	512.7		.7055	485.7
.7938	.1785	15	29.5	15	59.5	766.1	536.3		.6361	487.3
									Ave.	489.9
Tube D_2 : D = 5.739 cm.										
.1588	.0277	309[b]	432[d]	248	989	517.0	484.8		.9417	486.9
.3175	.0553	66	133	68	267	548.4	484.2		.8839	484.7
		67	134.5	67	268.5	551.4	486.8			487.4
.4762	.0830	32	64	31.6	127.6	582.9	486.1		.8266	481.8
.6350	.1106	19	37.6	19.3	75.9	625.7	494.5		.7701	481.9
.7938	.1383	13	26	13.3	52.3	673.4	505.6		.7145	481.1
		13	26.5	13.0	52.5	675.9	597.5			482.9
									Ave.	483.8
Tube E_1 : D = 6.554 cm.										
.1588	.0242	247	493	247	987	516.0	487.7		.9491	489.7
.3175	.0484	33.5[a]	133.5	66	233[g]	546.9	490.0		.8984	491.3
.4762	.0726	31	62.5	31.5	125	571.1	486.2		.8478	484.2
.6350	.0968	18.5	37.0	18.2	73.7	607.6	493.1		.7982	485.0
.7938	.1211	12.5	25.5	12.5	50.5	650.2	503.8		.7489	486.9
		12.5	25.2	12.6	50.3	647.6	501.8			485.0
									Ave.	487.0
Tube F_1 : D = 7.874 cm.										
.1588	.0202	243	488	246	977	510.2	486.6	486.1	.9575	488.5
.3175	.0403	64	132	62	258	529.2	482.6	480.9	.9153	484.4
.4762	.0605	30	60	—	90[h]	547.5	478.1	474.4	.8732	478.1[s]
.6350	.0806	17.5	35	17.8	70.3	578.9	485.1	478.8	.8315	481.3
.7938	.1008	11.5	23.8	12.2	47.5	610.8	491.9	482.3	.7900	482.6
		12.0	23.5	11.9	47.4	609.5	490.8	481.4	.7900	481.5
									Ave.	482.7
									Ave. All Tubes	485.4

[b] 5 cm. [a] 2 cm. [z] Highest value.
[d] 7 cm. [g] 14 cm. [s] Lowest value.
[h] 12 cm. * 16.02 for Tube F_1.

C. Failure of the Stokes Relation.

Inspection of Fig. 2 wherein are plotted data of Table 6 shows how badly Stokes' law fails for experimental systems throughout the range studied. When the Stokes values are plotted against d/D six curves are laid down (one for each tube) which are practically superimposed upon one another

FIG. 2.



Apparent viscosities calculated by several formulæ.

throughout the overlapping ranges. This is conclusive evidence that the true viscosity is some function of d/D which has only to be evaluated. The closest approaches to the accepted values come when d/D is smallest, the accepted values being the average of those calculated by the Faxen

relation (warrant for this will appear in later sections). When these curves are extrapolated to $d/D = 0$ values closely approximating the accepted viscosity are obtained. This is the condition of fall in a medium of infinite extent for which Stokes law is presumed to hold. Precisely similar curves may be plotted for Silicate *A*, which shows the highest viscosity ever so investigated. It follows that very much larger tubes or very much smaller balls, i.e., much smaller d/D values are required before wall effects can be experimentally eliminated. Essentially similar conclusions have been implied by Arnold,[16] Ladenburg, Sheppard and others.

For the calculation of η_S in Tables 5 and 6, t/S where t expresses time to fall S (16) cm. has been used for v of Eq. (2), and the factor .99703 introduced, permitting σ and ρ to be expressed in terms of specific gravities at 20° C./20° C. The factor includes correction for buoyancy of air. Formula (2) then takes the form

$$\eta_S = \frac{2}{9} \times 980.2 \times .99703 r^2(\sigma - \rho)t/S. \qquad (9)$$

D. The Ladenburg, Barr, Munroe and Lunnon Relations.

Viscosity values η_L of Tables 5 and 6 were calculated from the Stokes values by the relation

$$\eta_L = \eta_S/(1 + 2.4d/D). \qquad (10)$$

Values in some instances are given as calculated by the Barr formula which bears the following relation to the Stokes formula:

$$\eta_B = \eta_S/[1 + 2.4(d/D) + 2.4(d/D)^2]. \qquad (11)$$

Munroe has suggested a correction for lead shot falling in water which would lead to the following in terms of the Stokes values:

$$\eta_M = \eta_S[1 - (d/D)^{3/2}]. \qquad (12)$$

Lunnon suggests a correction to velocity which would lead to the following in terms of the Stokes values:

$$\eta_{Lu} = \eta_S[1 - .25(d/D)]. \qquad (13)$$

Both the Lunnon and Munroe corrections are advanced for conditions where the relations between inertia and the viscous force, i.e., the Reynolds numbers are much higher than for our work, over 1000 for Lunnon's experimental results.

Comparison of results is best made by reference to Fig. 2 for Silicate *B*. Ladenburg's attempt to correct the Stokes formula is a great improvement and gives results usually within ± 1 per cent. of the accepted averages for both silicates over the range of d/D up to .08. Some of the Ladenburg curves show minima at d/D = .04 to .07. Beyond .08 the corrections become more and more inadequate until at d/D = .3175 the viscosity calculated is over 40 per cent. too high. To avoid confusion in the figure only the *F* and *A* tube Ladenburg curves and only the *A* tube Barr curve have been drawn, the others taking the same relative positions as shown by the Stokes curves.

The Ladenburg correction for end effects may take the form

$$\eta_{L'} = \eta_L/(1 + 3.3r/h), \tag{14}$$

where h = height of the liquid column. This diminishes our η_L values from 0.3 to 1.5 per cent., a slight but inadequate improvement, and brings some values too low.

The Barr correction is a further but inadequate improvement and may give values somewhat more than 1 per cent. too low at values of d/D around .06.

The corrections indicated by Munroe and by Lunnon are much smaller than those applied by Ladenburg and hence beyond further consideration at this point.

E. The Faxen Formula.

Tables 5 and 6 and Fig. 2 also give viscosity values calculated by the Faxen formula

$$\eta_F = \eta_S F, \tag{8}$$

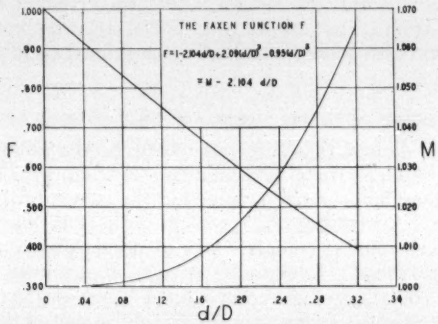
where $F = 1 - 2.104(d/D) + 2.09(d/D)^3 - 0.95(d/D)^5$. This complex relation may be evaluated easily by writing in the form

$$\begin{aligned} F &= [1 + 2.09(d/D)^3 - 0.95(d/D)^5] - 2.104(d/D) \\ &= M - 2.104(d/D) \end{aligned} \tag{15}$$

and reading the values of M from Fig. 3. The values of F also plotted here show the nature of the function.

In Fig. 2 the crosses indicate Faxen values for the complete range of experimental conditions. It is considered that the straight line drawn through these despite its slight slope represents a sufficient approach to the constancy desired under the wide range of conditions. The Y marks are the corresponding values divided by 10 for Silicate A, giving a still better degree of constancy.

FIG. 3.



It should be demonstrated that our conditions comply with the assumptions cited in connection with Eq. 5, namely, that R^2, $R(d/D)^2$, $(d/D)^6$ and R^2D/d are negligible compared to unity.

$(d/D)^6$. The maximum value of d/D from Tables 5 and 6 is .3175. $(d/D)^6 = 0.001024$.

R^2. The maximum value of R comes when velocity is highest, i.e. for 5/16″ ball in tube F_1 for Silicate B:

$$R^2 = \left(\frac{vd\rho}{\eta}\right)^2 = \left(\frac{Sd\rho}{t\eta}\right)^2$$

$$= \left(\frac{16 \times .7938 \times 1.701}{47.5 \times 485.4}\right)^2 = .00000088.$$

R^2D/d. Since the maximum value of $R^2 = .00000088$ and

the maximum value of $D/d = 1/.0202$, the maximum possible value of $R^2D/d = .00000088/.0202 = .000044$.

$R(d/D)^2$. The maximum value of R possible, combined with the square of the maximum value of d/D gives the following:

$$\frac{16 \times .7938 \times 1.701}{47.5 \times 485.4} \times (.3175)^2 = .000094.$$

With the exception of $(d/D)^6$ in a single case the conditions are well complied with.

It remains only to be shown that the constant viscosity values attained by use of the Faxen relation correspond accurately with measurements by the refined capillary tube technique.

COMPARISON OF FALLING SPHERE AND CAPILLARY TUBE RESULTS.

It was desired that agreement between the falling sphere and the capillary tube measurements be confirmed over the 10 to 10,000 poises range involved in the commercial work to be done. A considerable problem was thus encountered owing to the almost complete lack of standardizing materials over this range. Eventually it was determined best to measure the viscosities of Viscous Oil * and of glycerol † by our method and forward samples to the Bureau of Standards for checking. Armour & Co. kindly supplied viscosities specially measured by the capillary method at 20° and 22.5° C. for the glycerol.

Our data appear in Tables 7, 8 and 9. The viscosity values were calculated from the equation

$$\eta_F = \eta_S F = 13.614 r^2 t(0.99703\sigma - f\rho_T)F, \qquad (16)$$

which follows from Eq. (9) when corrections for specific gravity of the liquid at temperatures other than 20° C. are involved. Here ρ_T represents specific gravity of the liquid relative to water at temperature T and f is the relative density of water at that temperature less the buoyancy of air. The

* Obtained from Standard Oil of California. A remarkably stable, very light amber oil of enormous viscosity.

† Armour's Super C.P. Glycerine, 97.90% glycerol.

TABLE 7.
Viscosity Data on Glycerol. Tube A_2 : D = 2.516 cm.

Temp. ° C. ± .02.	Ball *d*, cm.	*d*/*D*.	Sec. to Fall 16.00 cm.	ρ, $\frac{T^\circ}{T^{20}}$.	η_F.	η_F, Ave.
22.50	.1191	.0473	26.38	1.257	7.459	7.477
22.50	.1588	.0631	15.4	1.257	7.494	
20.00	.1191	.0473	32.65	1.258	9.232	9.249
20.00	.1588	.0631	19.05	1.258	9.267	
10.00	.1191	.0473	85.7	1.262	24.210	24.24
10.00	.1588	.0631	49.9	1.262	24.270	
0.00	.1191	.0473	260.5*	1.268	73.500	
	.1588	.0631	148.	1.268	71.920	
	.3175	.1262	43.73	1.268	71.110	

* Small bubble interfered. Apparent effect seems too large.

coefficient of expansion of steel being so small, no correction to the 20°/20° specific gravity σ is required. The formula holds for fall of 16.00 cm.

Tables 7 and 8 give viscosity data and results calculated by the Faxen relation over the range 7.5 to 11,600 poises, a much wider range than hitherto studied. From two to six *d*/*D* values are represented for each viscosity measured, ranging from .0461 to .2540 and confirming further the constancy of the values calculated over a wide range of experimental conditions. Table 9 compares the averaged values against Bureau of Standards and Armour & Co. values. The viscosity of the oil at 0° C. was reported outside the range of the Bureau's instruments.

It appears from Tables 7, 8 and 9 that with apparatus and methods of the refinement used the falling sphere method is capable of measuring absolute viscosity over the range 7.5 to 3660 poises to an accuracy of plus or minus one per cent. Half of our measurements agree to better than one-half of one per cent. The hope is expressed that measurements may be made to better than one-half of one per cent., perhaps even two-tenths of one per cent. over some ranges, given apparatus of quite attainable refinement.

TABLE 8.
Viscosity Data: Viscous Oil.

Temp. ° C. ± .03.	Ball d, cm.	Tube.	d/D.	Sec. to Fall 16 cm.	ρ, $\frac{T^\circ}{T^{\circ\cdot}}$	η_F.	η_F, Ave.
50.00	.1588	A_1	.0635	195.2	.889	100.33	
	.3175		.1270	57.85		99.54	99.89
	.1588	B_1	.0461	186.7		100.06	
	.3175		.0923	52.85		99.64	
40.00	.1588	A_1	.0635	423.05	.890	217.4	
	.3175		.1270	125.25		215.5	216.1
	.1588	B_1	.0461	403.6		216.1	
	.3175		.0923	114.3		215.4	
30.00	.3175	A_1	.1270	293.25	.893	503.9	
	.4762		.1905	158.28		504.1	504.6
	.3175	B_1	.0923	268.0		504.4	
	.4762		.1384	136.45		506.0	
22.50	.3175	A_1	.1270	585.0	.895	1005	
	.4762		.1905	316.0		1006	1005
	.3175	B_1	.0923	534.0		1005	
	.4762		.1384	271.0		1005	
20.00	.3175	A_1	.1270	746.0	.896	1281	
	.4762		.1905	402.0		1279	
	.6350		.2540	274.6		1280	1279
	.3175	B_1	.0923	681.0		1281	
	.4762		.1384	344.0		1275	
	.6350		.1845	219.0		1279	
20.00*	.3175	A_1	.1270	751.0	.896	1289	
	.6350		.2540	276.1		1287	
	.3175	B_1	.0923	685.0		1288	1288
	.6350		.1845	220.0		1285	
	.3175	C_1	.0710	651.5		1291	
15.00*	.3175	A_1	.1270	1253.0	.898	2150	
	.6350		.2540	457.0		2130	
	.3175	B_1	.0923	1140.0		2143	2142
	.6350		.1845	367.0		2142	
	.3175	C_1	.0710	1083.0		2147	
	.6350		.1420	323.5		2137	
10.00	.3175	A_1	.1270	2129.0	.900	3652	
	.4762		.1905	1145.5		3642	3639
	.3175	B_1	.0923	1938.0		3642	
	.4762		.1384	978.0		3621	
0.00	.3175	A_1	.1270	6780.0	.905	11,620	
	.4762		.1905	3647.0		11,585	11,581
	.3175	B_1	.0923	6160.0		11,565	
	.4762		.1384	3123.0		11,554	

* Measured on 1 qt. original sample received. Other values measured on 5 gal. lot received later. Both lots carry the same maker's test number and are presumed identical, especially in view of the concordance of results obtained, as above.

TABLE 9.
Comparison of Falling Sphere—Capillary Tube Viscosities.

Temp. ° C.	Viscosity, Falling Sphere.	Viscosity, Capillary Tube.	Difference.
	Glycerol.		
22.50	7.477 poises	7.43 poises	+ .63%
20.00	9.249	9.26	− .12
10.00	24.24	24.1	+ .58
0.00	71.52 ‡	72.1	− .80
0.00	72.18 *	72.1	+ .11
	Viscous Oil.		
50.00	99.89	100	− .11
40.00	216.1	217	− .41
30.00	504.6	507	− .47
22.50	1,005	1007	− .20
20.00	1,279	1290	− .85
20.00	1,288 ‡	1290	− .16
15.00	2,142 ‡	—	—
10.00	3,639	3660	− .57
0.00	11,581	—	—

‡ Ave. for balls of 2 sizes.
* Ave. for balls of 3 sizes.
‡ Original 1 qt. sample.

We have still to evaluate the terms R^2, R^2D/d, $R(d/D)^2$ and $(d/D)^6$ in connection with the data of Tables 7 and 8. All but R^2D/d prove well below the value .001 previously assumed negligible in comparison with unity. Here we find:

Temp.	d.	η_F.	$R^2 D/d$.
22.50° C.	.1588	7.477	.0121
22.50° C.	.1191	7.477	.0031
20.00° C.	.1588	9.26	.0053
20.00° C.	.1191	9.26	.0013

The values of this term are taken account of in the more general Faxen relation (Eq. 5). When calculations are made for the correction to the Stokes values by the two methods the difference proves altogether negligible here or even for glycerol solutions of 4.5 poises or lower. We are justified in using the simplified relation throughout this work both mathematically and practically therefore since our agreement with

capillary tube methods is just as satisfactory at the lowest as at any other part of the viscosity range.

SUMMARY.

1. The effect of failure to comply with the assumption of motion in a medium of infinite extent involved in Stokes' law for the calculation of viscosity by the falling sphere method has been investigated.

2. The range of experimental conditions covered is as follows:

Balls Used: 3/64 to 5/16" (.1191 to .7938 cm.) steel bearings.
Tubes Used: 2.500 to 7.874 cm. I.D.
Ratio of Diameters of Balls to Tubes: d/D: .0202 to .3175.
Velocities of Fall: .000157 to 1.39 cm./sec.
Reynolds Numbers: 5.9×10^{-3} to 2×10^{-2}.

3. Apparent viscosities calculated by the Stokes relation for a given liquid at fixed temperatures are a function of the ratios of diameter of sphere to diameter of tube alone, and increase rapidly as this ratio increases.

4. The Ladenburg correction to the Stokes formula, equivalent to dividing the Stokes values by $(1 + 2.4d/D)$, gives apparent viscosities within about 1 per cent. of the accepted viscosity over the range of ratio of diameters .02 to .08 but they become 40 per cent. too high at the highest values of the ratio investigated.

5. The Ladenburg correction for end effects, equivalent to dividing the above Ladenburg values by $(1 + 3.3r/h)$, diminishes these values by not more than 1.5 per cent. for our apparatus.

6. The Barr correction, equivalent to dividing the Stokes values by $[1 + 2.4d/D + 2.4(d/D)^2]$, applies too great a correction over a limited range at $d/D = .06$, where the function appears to show a minimum. At d/D values greater than .10 the correction is too small.

7. The Faxen relation which is equivalent to multiplying the Stokes values by $[1 - 2.104d/D + 2.09(d/D)^3 - .95(d/D)^5]$ gives values within 1 per cent. of the absolute viscosities measured by the capillary tube method over the whole range checked (7.5 to 3660 poises).

8. The Faxen treatment of the hydrodynamic theory puts the falling sphere method on a basis probably as sound mathematically as that upon which the capillary tube technique rests.

9. The falling sphere method is so simple that unless highest accuracy is desired apparatus found in any laboratory may be made to serve.

10. The method is adaptable to a wide range of experimental conditions and is particularly suited for liquids of 10 poises viscosity and upward.

LITERATURE CITED.

1. HERSEY, M. D., J. FRANK. INST., **219**, 677–700 (1935).
2. STOKES, G., *Trans. Cambridge Phil. Soc.*, Vol. 8 (1845), Vol. 9 (1851); Collected Papers, Vol. 1.
3. LADENBURG, R., *Ann. Physik.*, **22**, 287 (1907); **23**, 447 (1907).
4. OSEEN, C. W., *Arkiv. f. Mat., Astron. och Fysik.*, **6**, No. 29 (1910); **9**, No. 16 (1913).
5. FAXEN, H., Dissertation, Upsala (1921).
6. FAXEN, H., *Ann. Physik*, **68**, 89 (1922); *Arkiv. f. Mat., Astron. och Fysik*, **17**, No. 27 (1922).
7. BARR, GUY, "Monograph on Viscometry." Oxford (1931).
8. LIEBSTER, H., *Ann. Physik.*, **82**, 541–562 (1927).
9. SCHMIEDEL, J., *Phys. Zeits.*, **29**, 593 (1928).
10. HATSCHEK, E., "The Viscosity of Liquids." Bell, London (1928).
11. BINGHAM, E., "Fluidity and Plasticity." McGraw-Hill (1922).
12. TIETJENS, O. G., "Applied Hydro- and Aero-Mechanics." Translated by J. P. Den Hartog. McGraw-Hill (1934).
13. BULKLEY, R., *Bur. Std. J. Research*, **6**, 89–112 (1931), Research Paper No. 264.
14. SHEPPARD, S. E., *Ind. Eng. Chem.*, **9**, 523 (1917).
15. GIBSON, W. H. AND JACOBS, L. M., *J. Chem. Soc.*, **117**, 473 (1920).
16. ARNOLD, H. D., *Phil. Mag.*, **22**, 755–775 (1911).

Device Measures Effectiveness of Pipe Line Coating.—(*Oil and Gas Journal*, Vol. 34, No. 29.) Corrosion is the enemy of all who have to do with underground pipe lines. Technical knowledge and experimentation have brought forth various coatings and wrappings for buried pipe. To determine the effectiveness of the pipe covering in combating corrosion without the necessity of uncovering the pipe, is the object of an electrical device invented and developed by A. L. Smith of Houston, Tex. Mr. Smith in conjunction with Crutcher-Rolfs-Cummings, Inc. has been conducting a series of practical tests with the device, results of which have been marked with success. The apparatus consists of a high frequency transmitter and a receiving instrument for measuring electrical flux density, both of which are portable. The transmitter, one terminal of which contacts the pipe and the other connects with a ground rod located some distance to the side of the line, charges the pipe. The receiving instrument is carried along the line and, through a ground contact made at desired intervals, reacts to current discharges from the pipe in proportion to the current density in the soil around the pipe. The instrument has many possibilities. It may be used, by utilizing the principle of two ground rods, for determining, in advance of pipe laying, the corrosive areas on proposed rights of way. Similarly in consideration of cathodic protection for sections of pipe lines, it will serve to check conditions of coating with respect to conductance. Oil leaks or "collar sweats" on bare lines not visible on the surface also can be located by the instrument. Experiments now are being made to prove possible utilization of this new principle of measuring flux density in determining the geological nature of strata in drilling wells.

R. H. O.

"Was it not Dr. Johnson who even reproached Benjamin Franklin with collecting electricity in a bottle while such trifles as wars and political fortunes of the nations were left to pass unnoticed?"—J. M. Clarke.

THE VARIATION OF COSMIC RAY INTENSITY WITH DIRECTION IN THE STRATOSPHERE.*

BY

W. F. G. SWANN and G. L. LOCHER.

BARTOL RESEARCH FOUNDATION

Communication No. 92.

A large stratosphere balloon with attached gondola provides conditions unobtainable by any other means so far developed for certain types of cosmic ray measurements at high altitudes. The measurement of directional intensities necessitates holding the balloon at constant altitude for a considerable time. It necessitates the maintenance of a reasonable constancy of level. It necessitates a control on the rotation of the balloon so that data may be secured at various azimuths.

WEIGHT AN ESSENTIAL FEATURE.

The type of apparatus necessary for the work cannot readily be reduced beyond a minimum weight which is fairly large, if the observations are to obtain the maximum dependability desired. In the case of some experiments, moreover, particularly those having to do with the measurement of nuclear bursts, weight is an essential feature quite apart from the mechanisms associated with the measurement, for one must carry enough of the substance for the cosmic rays to bombard to secure sufficient data on the results of such bombardment within a reasonably limited time.

Even in a manned-balloon stratosphere flight the recording apparatus should be rendered so automatic in its action that practically nothing but the turning on of one or two switches should be required of the observer in charge, in order that he be left free to attend more carefully to matters of a purely ballooning nature such as that of retaining constant altitude, that of providing for rotation, and the like. It is, of course, not absolutely impossible to provide even for features such as these by automatic means, and so handle the problem with an unmanned balloon. However, there is a limit to the

* Reprinted from National Geographic Society Contributed Technical Papers, Stratosphere Series, Number 1.

amount of inanimate mechanism which it is desirable to associate with the apparatus, and there is a point beyond which the simplest form of automatic mechanism for securing the end desired is a man. After all, a man does not contribute more than a fraction of the weight which it is desirable to carry in the form of apparatus.

The investigations of recent years have taught us that cosmic rays consist, at any rate in part, of electrically charged particles hurled into our atmosphere from outer space with such enormous energies that electrical potential differences of the order of a thousand million and even ten thousand million, or more, volts would be necessary to give them that energy. The paths of these particles are bent by the influence of the earth's magnetic field as they approach the earth; for, although that magnetic field is relatively weak, it extends over great distances, and the cumulative effect on even these high-energy particles in their approach toward the earth is very considerable. As a matter of fact it is so considerable that charged particles with energies less than that which they would receive under ten thousand million volts would be unable to reach the earth at the equator before they were swung back into space by the earth's magnetic field. The flight of a stream of charged particles constitutes a current of electricity and the sidewise thrust on the beam, which results in its bending, is the same thrust as that which the electromagnet of a motor produces on the wires of the armature, causing their rotation.

CHARGED PARTICLE RAYS BENT BY EARTH'S MAGNETIC FIELD.

The effect of the earth's magnetic field is to cause the charged particle rays to come to us with different intensities from different directions. The effect of the earth's magnetism depends in magnitude upon the energies of the rays; and the complete story of these effects at different altitudes contains much information on the nature of the rays, their absorbability in passing through the atmosphere, and so forth.

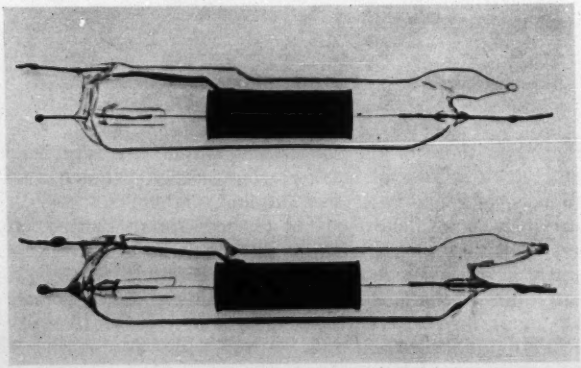
Then, quite apart from the effect of the earth's magnetism, the intensity of the rays decreases from the zenith to the horizontal on account of the increase of thickness of the atmosphere through which they must pass in the more horizontal directions. The variation of this phenomenon with

altitude gives much information about the nature of the rays at different altitudes and about their absorbability in the atmosphere.

The apparatus designed for the National Geographic Society-U. S. Army Air Corps Stratosphere Flight constituted, in effect, a battery of cosmic ray telescopes arranged to be pointed in different directions and so to record the intensities of corpuscular cosmic rays from those directions. The construction of a cosmic ray telescope, which is of course not a new appliance, depends upon the use of what is called a Geiger-Müller counter. Such a counter consists, essentially, of a glass tube containing a hollow metal cylinder along the axis of which runs a fine wire, the tube being filled with a suitable mixture of gases at about one tenth of an atmosphere pressure.

When the wire and cylinder are connected to the terminals of a battery of sufficiently high voltage, an electric discharge takes place. If the voltage is not quite high enough, no such discharge occurs, but under these conditions the gas is in a very sensitive state, so that the passage of a single corpuscular cosmic ray through it will precipitate a discharge in which the equivalent of an electric spark occurs between the wire and

FIG. 1.



Counters used in the cosmic-ray telescopes. Figure 1, above, shows two Geiger-Müller counters in line. Each counter consists of a glass tube containing a hollow metal cylinder along the axis of which runs a fine wire. (See text below.)

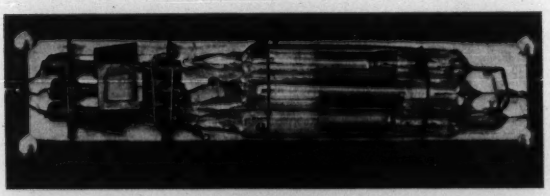
cylinder of the tube. This discharge carries with it a definite quantity of electricity, which, by means of suitable radio amplifying devices, may be made to record itself in any manner desired.

A single counter has the disadvantage that it will respond to rays such as those from radioactive impurities in the atmosphere, as well as to cosmic rays. Moreover, it will respond to rays from any direction. If, however, two such counters are placed in line as in Fig. 1, it is possible to devise an electrical circuit, to be used in conjunction with the counters, such that a record will be made only when both tubes discharge simultaneously. In this case the apparatus records only those rays which come in such a limited cone of directions as to include both counter tubes.

APPARATUS LIKE TELESCOPE.

In other words, the apparatus has the characteristic of a telescope, a telescope, moreover, which is unaffected by rays

FIG. 2*A*.



A counter unit.

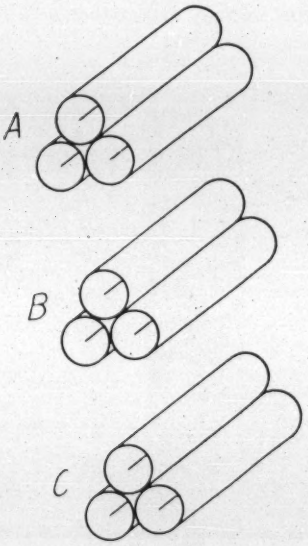
other than those of the corpuscular cosmic ray type, since none but these are capable of passing through as much material as is contained in the two tubes in tandem.

For reasons which it will be unnecessary to discuss here, it is desirable to use three units in tandem and to arrange so that a record is made only when the counting tubes of all three units discharge simultaneously. Moreover, it is desirable, again for reasons which are rather involved, to replace each individual counting tube by three which lie side by side, and act as one single counter.

Figure 2*A* is a picture of one of these counter units used

in our apparatus. The three individual counter tubes act, in effect, as one. Figure 2*B* represents an end view of three of these counting units arranged in line so as to constitute a cosmic ray telescope which takes in all rays which pass through

FIG. 2*B*.



End view of counter units.

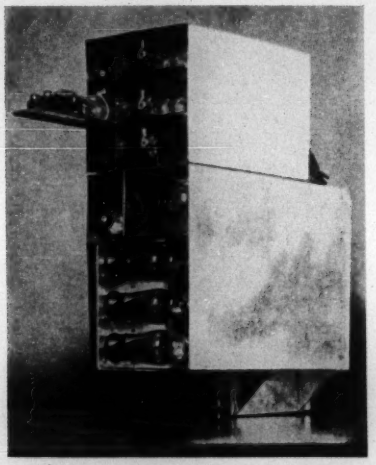
the two areas comprised by the three counting tubes of *A* and the corresponding counting tubes of *C*.

Two such telescopes were used side by side for each of the angles investigated. They were disposed as indicated in Fig. 3, page 280, where the rest of the box contains the electrical equipment associated with the amplifying tubes, etc. There were four such boxes, one for the vertical direction, one for the horizontal, and one for each of the angles 30° and 60° from the zenith. Then the whole apparatus was duplicated for each of these angles with a certain addition whose nature and purpose will now be described.

"WALL" OF COUNTERS PROVIDED.

While the three elements of a telescope combine to produce a record only when they discharge simultaneously, there is a limit to the meaning of the word "simultaneous." That limit is imposed by the electrical characteristics of the apparatus; and, if as is the case, the cosmic rays travel to some extent in groups, we may expect that occasionally the three

FIG. 3.

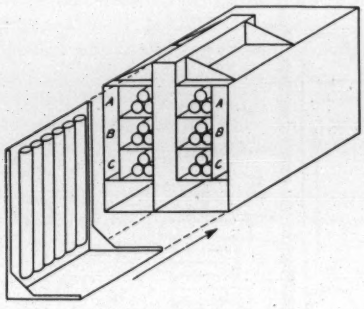


Box containing two sets of counters and electrical equipment.

elements A, B and C, Fig. 2B, for example, will be discharged simultaneously, not by a single ray which passes through all three, but by three independent rays coming in sidewise, for example, in such a way that one discharges A, another discharges B, and another discharges C. For this reason, in the duplicate sets to which we have referred, a sort of "wall" of counters was provided and disposed in such a manner that it was impossible for rays to pass through the counting tubes in directions other than the approximately axial directions, without passing through this wall of counters.

The electrical apparatus was then arranged so that the simultaneous discharge of any counter in the "wall" annulled records which would otherwise be made by the non-collinear rays discharging the three counter elements simultaneously. Figure 4 shows one of the counting sets with this protective

FIG. 4.



Counting set showing protective wall.

wall in position. For each of the four angles there was one set with the wall and one without, so that it was hoped to gather information in a fo[illegible]ncontaminated by the effects of groups of rays and at [illegible]me time to obtain the effects of these groups.

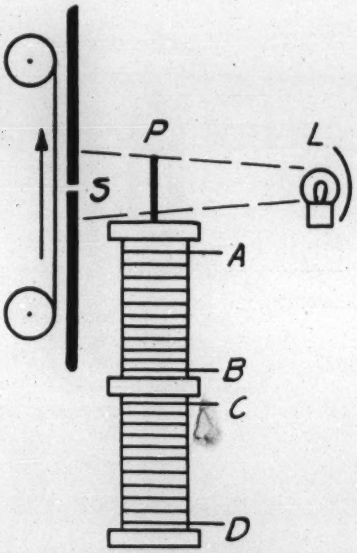
RECORDS MADE IN TWO INDEPENDENT MANNERS.

Each of the eight pairs of telescopes was made to record the number of cosmic ray corpuscles going through it, in two independent manners. In one of these a modified watch was used in such a way that each count resulted in the passage of one tooth of a cog by the escapement lever. The markings on the faces of the watches were replaced by pin-heads and the dials were blackened. The whole assembly of watches was photographed upon moving photographic paper once every twenty seconds during the observations, and on the same record was obtained the photograph of the dial of a mariner's compass giving the azimuth of the gondola and a photograph of a real watch so that the time could be obtained,

and consequently the altitude by a comparison with the pilot's log.

The second method of recording will be understood by reference to Fig. 5. *AB* is a solenoid carrying a constant current. It supports in space a piece of iron rod shown by

FIG. 5.



Solenoid system for photographic recording.

the black line. The lower end of this rod dips into the end of another solenoid which becomes excited when it receives a pulse of current from one of the counter sets. The excitation of the lower solenoid results in a sudden dive of the iron rod. There was one of these solenoid systems to correspond to each of the eight counter systems.

A beam of light falling upon the upper ends of the iron rods caused eight shadows of these rods to fall upon a horizontal slit, behind which photographic paper moved continuously in a vertical direction. In the absence of any pulses,

the eight shadows showed as eight vertical white lines on the developed photographic paper. When a counter pulse occurred, the corresponding iron plunger dived down, permitting the momentary passage of light onto the slit, resulting in a black interruption of the corresponding white line, on development. In this manner each counter pulse was caused to record itself as an interruption of one of the white lines.

This system makes it possible to observe simultaneous discharges of two or more telescopes due to "showers" of rays coming from cosmic ray nuclear disintegrations, particularly those produced in the massive material contained in the gondola. The iron plungers moved with extreme rapidity, so that the system was capable of counting a large number of rays per minute.

Since a very slight tilt in the vertical direction produces a change of cosmic ray intensity of amount comparable with that produced by a considerable rotation in the horizontal direction, it was very necessary to keep the apparatus as horizontal as possible, or at any rate to know how much it departed from the horizontal in the plane containing the axes of the telescopes. For this reason a sort of pendulum was constructed with a small electric lamp at the position of the bob.

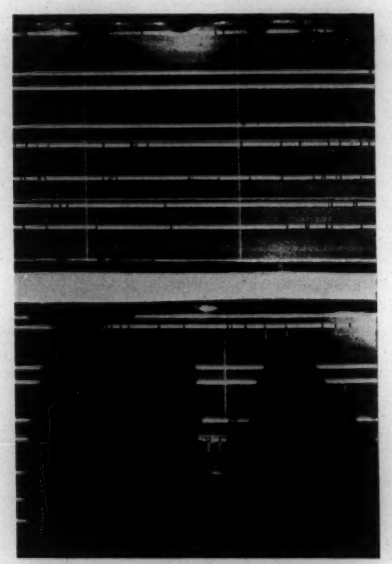
An image of the filament of this lamp traced a line upon the photographic paper; the departure of this line from a standard position gave the tilt of the gondola at any instant. The photographs of the watch-recorders, level, compass and time were obtained on one record, while the solenoid recorder utilized another record. There were thus two photographic records and two corresponding cameras.

RESULTS OBTAINED BY THE RECORDS.

As a result of the catastrophe, the former of these records was completely destroyed, but the latter was salvaged in a condition showing that it had been partially exposed to light. It was sent to the Eastman Kodak Company, whose staff kindly exerted their best efforts upon it. While a lot of the information originally desired has been lost, we have secured, nevertheless, what we regard as certain very valuable pieces of information.

Figure 6 shows, in two places, the actual record taken at 40,000 feet, one place where it is fogged very badly, and another where it is more or less clear. The white lines crossing the record vertically represent twenty-second intervals. Even where a portion of the record has been lost by

FIG. 6.



Cosmic ray records made photographically at an altitude of 40,000 feet.

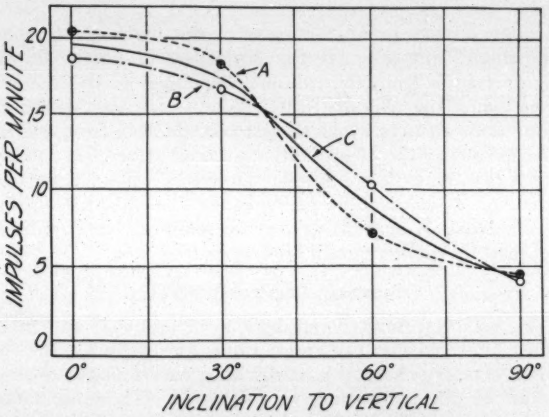
fogging, it is possible to take the individual parts of any one of the white lines and obtain from them the average number of counts per second during the period of the observations.[1] Figure 7 shows the intensity of the cosmic radiation plotted

[1] It will be observed that there are in all ten horizontal white lines. Two of them were for subsidiary purposes which might arise, other than those connected with the counters. In actual practice they were not used, so that two of the traces show no cosmic ray counts.

against the angle from the zenith. The curve A corresponds to the data obtained from the sets without the shielding wall of counters. Curve B corresponds to the data for the other sets.

The zenith point for curve A had to be filled in by general correspondence of the shapes of the two curves, rather than from actual observation, since, in the first place, the trace corresponding to this point fell at the extreme edge of the

FIG. 7.



Intensity of cosmic radiation plotted against the angle from the zenith.

photographic paper and was very badly fogged, and, in the second place, there were certain other reasons to doubt the observations on this particular point.

Had the apparatus descended intact so that it would have been possible to standardize the various counting telescopes in relation to each other, it would have been interesting to discuss the relationship between curves A and B, of which A is for the telescopes that were protected against non-collinear groups of rays, and B is for the sets that were not shielded against them. Under existing circumstances, however, it is perhaps unwise to base too much discussion on the significance

of the difference of these two curves. It is, however, of interest that the intensity for the horizontal direction is practically the same for the two curves, indicating that the number of these rays was largely unaffected by showers.

The significant features obtained from the present observations are illustrated by the thick curve, *C*, which represents the average of curves *A* and *B*. Its most significant feature is the relatively large values of the intensity in the horizontal direction. At sea level the intensity in the horizontal direction is negligible compared with that in the vertical. This arises from the fact that the horizontal rays have to travel through a very great thickness of the earth's atmosphere. One might suppose that the horizontal intensity shown in Fig. 7 results from the finiteness of angle of the telescope. Even when the axis of the telescope is horizontal, the telescope takes in rays which depart considerably from the horizontal, so that the effective thickness of atmosphere through which rays reach it is limited. However, when the matter is submitted to calculation, we find that this effect alone should be incapable of accounting for the relatively large intensity recorded by the horizontal telescope.

SECONDARY RADIATION IMPORTANT

It has been pointed out by one of us [2] that the entities which affect cosmic ray counters are probably for the most part secondary charged particles shot out from the atoms of the air by the more energetic primaries. These secondaries have energies, which, while high, are so low compared with the primaries that they never could have reached the earth had they started from infinity since they would have been turned back by the earth's magnetic field. Starting from some point in the higher regions of the atmosphere, however, they travel in a curved path. The radius of the path of electrons of 1,000-million volts energy would be about 50 kilometers.

In the lower regions of the atmosphere such rays could not travel far enough to be bent through an appreciable angle. Coming from regions above 40,000 ft., however, a 1,000-

[2] W. F. G. Swann, "On the Nature of the Primary Cosmic Radiation," *Phys. Rev.*, **43**, 945–946, 1933.

million volt electron would not lose more than 50 per cent. of its energy in traveling a distance so large that in that distance its path would be bent through a right angle. We thus see how it is possible for rays incident more or less vertically and even at other angles upon our atmosphere to be bent around so as to enter in a horizontal direction at an altitude of 40,000 ft. We believe that the surprisingly high intensity at 40,000 ft. for the horizontal direction shown in our experiments is representative of the action of the earth's magnetic field in bending the paths of these secondary rays.

INCREASE OF IONIZATION WITH ALTITUDE.

Most former investigations of cosmic ray intensity at high altitudes have been obtained by measuring the rate at which ions are produced in a closed vessel filled with some gas such as argon. These ions are of course positively and negatively charged particles produced by the bombardment of the atoms of gas by the cosmic rays or their subsidiaries. Now by taking account of all directions as given by such curves as Fig. 7 for sea level and for 40,000 ft., it is possible to compare the amount of ionization to be expected in a closed vessel at these two levels on the hypothesis that the ionization is produced entirely by the rays which are measured by the counters. If we do this we find that the ionization should increase from sea level to 40,000 ft. by a factor of 64. Direct measurements by Professor Millikan's apparatus in the Settle Flight gave 250 ions per cc. per second at this altitude. The increase of the ionization in a closed vessel from sea level to 40,000 ft. would consequently correspond to that given by the counters if the value at sea level for ionization chambers were 3.9 ions per cc. per second.

The sea level value given by Millikan is 2.4, that by Compton is 1.9, and that by Hoffmann 1.0. Even the value 2.4 is not sufficiently in agreement with 3.9 to warrant us in believing that the ionization and counter data correspond. On the other hand, if we should take the value 1.0 ions per cc. the increase of ionization from sea level to 40,000 ft. as indicated by counters, would fall considerably short of that given by ionization chambers. Since the National Geographic Society-U. S. Army Air Corps Flight, the Jean Piccard Flight

has been made, and has given further data. It is now possible to compare the data at 53,000 ft. with those at 40,000 ft. without invoking the values at sea level. If we do this we find that the ratio of the ionization at these two altitudes is 1.7 as given by Millikan's results from the Settle Flight, and 1.9 as obtained from our counter data for the Piccard Flight and the National Geographic Society-U. S. Army Air Corps Flight.

If we should be forced to accept the conclusion that increase of ionization with altitude as measured by ionization chambers is considerably greater than the corresponding increase as deduced from counter data, we should be faced with the necessity of considering the origin of such an apparent discrepancy. In this connection the following speculations may give interest. We have reason to believe that a portion of the ionization occurring in a gas is produced by entities other than those which could discharge a cosmic ray telescope. In fact, one of us has shown and discussed [3] the nature and significance of such entities which are to be found in the showers of rays produced by the bombardment of matter by primary cosmic rays.

PRIMARY, SECONDARY, AND TERTIARY RADIATION.

When a primary cosmic ray suffers an impact with an atom, we may suppose that there is a certain ratio between the numbers of ordinary secondary electron-rays produced and the numbers of these nuclear entities, as we shall call them. The secondary rays also bombard atoms and give rise to tertiary electron-rays and nuclear entities. Certain theoretical considerations suggest that the ratio of the number of nuclear entities to those of the electron type may increase with the energy of the primary rays causing them, and that the capacity of the secondary electron-rays for producing nuclear entities should increase with the energy of the primaries. If this is the case, we can see why it may be that in the stratosphere, where the primary rays are of higher energy than they are on the average at the earth's surface, we should find a

[3] G. L. Locher, "Cloud Photographs of Cosmic-Ray Stösse," JOUR. FRANK. INST., 216, 673–682, 1933. Also, G. L. Locher, "Neutrons of High Energy from Cosmic Ray Bursts in Aluminum," *Phys. Rev.*, 45, 296, 1934.

greater proportion of these nuclear entities which do not affect the counters; and we see, moreover, why the ionization in a closed vessel, determined as it is in part by these nuclear entities, should be more affected by altitude than is the portion of the radiation detected by counters. Whatever the facts may ultimately turn out to be as regards comparison of the counter data with enclosed vessel data, we conclude that observations of cosmic ray intensity in the stratosphere, as measured by counters, when compared with those given by ionization chambers, throw a very important light upon the nature of the entities resulting from the cosmic rays and participating in ionization phenomena.

Finally, while the catastrophe to the balloon has prevented us from learning as much as we had hoped to learn from these observations, it has given us enough to point out the nature of the experiments which would have the greatest value in another flight. In fact, the information which it has provided for us in this connection, is comparable with that which would have been provided had the flight been completely successful.

For our standard timepiece we are indebted to the Hamilton Watch Company. We wish to express our appreciation to the Electric Storage Battery Company for the donation of the wet-cell batteries, and to the Burgess Battery Company for the dry-cell batteries used in the work. Nearly all of the radio tubes used in the Geiger counter apparatus were kindly donated by the Radio Corporation of America.

Phenothiazine.—(*Food Industries*, Oct. 1935, p. 492.) So far arsenic and lead sprays have proven most practical for protecting growing foodstuffs from the ravages of insects. On the other hand, the grower of fruit, has found the advantages of lead arsenate spray protection to be offset largely by the difficulty and expense attendant to the removal of the spray residues so that his produce shall be fit to market and safe for human consumption.

In order to assist the grower, the Bureau of Entomology of the Department of Agriculture has investigated a large number of organic materials and has found at last one which apparently is just as good an insecticide as lead arsenate but offers none of the difficulties of spray residue. This material is phenothiazine, an organic chemical synthesized by fusing together one part of diphenylamine with two parts of sulphur at 180° C. using iodine as a catalyst. Purified by recrystallizing from toluene, phenothiazine is a light yellow powder, neutral in reaction, insoluble in water, and only slightly soluble in cold oil or the usual organic solvents.

This new insecticide may be applied as a dust for dry treatment if desired; but the preferred application is a suspension in water containing a wetting or adhesive medium. Phenothiazine is nontoxic to man and to all warm-blooded animals. This means that the grower has no problem of preventing stock from access to foliage or fruit which has been treated. It has been found that the spray, though reasonably adhesive to accomplish its insecticidal purpose, brushes or washes from the fruit and vegetable quite readily.

C.

"The advantages of organization in research are shared alike by the institution that maintains the research and by the men who do the research."—T. A. Boyd, "Research."

NOTES FROM THE NATIONAL BUREAU OF STANDARDS.*

INTERNATIONAL COMMITTEE ON WEIGHTS AND MEASURES.

The International Committee on Weights and Measures held its regular biennial meeting at Sevres and Paris, France, October 1 to 8, 1935. Its actions of most general interest concern the adjustment of values of the electrical units to make them concordant with the fundamental mechanical units.

The eighth general conference in 1933 gave the international committee power to fix new values of the electrical units and the date for their adoption. It was expected that the new values would be established provisionally in 1935, (Technical News Bulletin 200; December, 1933), but reports presented to a meeting of the Advisory Committee on Electricity, September 24 to 27, indicated that several years more would be required to complete the experimental determinations considered necessary to give a satisfactory basis for the units. The international committee therefore adopted the following resolutions (translated from the official French text):

1. The international committee decides that the definitive date on which the absolute practical system of electrical units shall be substituted for the (present) international system shall be January 1, 1940.

2. The Advisory Committee on Electricity is given the duty of establishing, not later than February, 1939, the ratios between the new absolute units and the corresponding international units.

3. The meetings of the advisory committee and of the technical subcommittee planned for the year 1937 shall be held for the purpose of fixing provisional values of these ratios.

4. In the final establishment of these ratios there shall be considered only those definitive results of abso-

* Communicated by the Director.

lute measurements which shall have been reported to the advisory committee before the end of 1938.

5. These ratios shall be certified to the governments of the different countries not later than March, 1939.

6. The new values of the electrical standards thus established shall hold for a period of at least 6 years from January 1, 1940.

The international committee also approved the following statement for general publication:

1. In accordance with the authority and responsibility placed upon it by the General Conference on Weights and Measures in 1933, the International Committee on Weights and Measures has decided that the actual substitution of the absolute system of electrical units for the international system shall take place on the 1st of January, 1940.

2. In collaboration with the national physical laboratories, the committee is actively engaged in establishing the ratios between the international units and the corresponding practical absolute units.

3. The committee directs attention to the fact that it is not at all necessary for any existing electrical standard to be altered or modified with a view to making its actual value conform with the new units. For the majority of engineering applications the old values of the international standards will be sufficiently close to the new for no charge, even of a numerical nature, to be required. If for any special reason a higher precision is necessary, numerical corrections can always be applied.

4. The following table gives a provisional list of the ratios of the international units to the corresponding practical absolute units, taken to the fourth decimal place. Since differences affecting the fifth decimal place exist between the standards of the international units held by the various national laboratories and also because all the laboratories which have undertaken determinations of the values of their standards in absolute measure have not yet obtained final results, the com-

mittee does not consider it desirable for the present to seek a higher precision. At the same time it hopes that it will be possible to extend the table of these ratios with a close approximation to the fifth decimal place well before the date fixed for the actual substitution of the practical absolute system for the intenational system.

With a view to reconciling the differences now existing between "international" units as maintained in different countries, the French laboratory, which was most divergent, announced that it would accept the mean of the other five principal laboratories, and proposed that other countries do the same. The remaining differences, however, are a very few parts in 100,000, and in view of the prospective change to the absolute units within a few years the National Bureau of Standards did not think it wise to confuse the records by an intermediate adjustment of units.

TABLE.

1 Ampere	International	= 0.999 9	Ampere	Absolute
1 Coulomb	"	= 0.999 9	Coulomb	"
1 Ohm	"	= 1.000 5	Ohm	"
1 Volt	"	= 1.000 4	Volt	"
1 Henry	"	= 1.000 5	Henry	"
1 Farad	"	= 0.999 5	Farad	"
1 Weber	"	= 1.000 4	Weber	"
1 Watt	"	= 1.000 3	Watt	"
1 Joule	"	= 1.000 3	Joule	"

At a meeting in June, 1935, the International Electrotechnical Commission had decided to adopt the Giorgi system of units based upon the meter, kilogram, second, and a fundamental electrical unit to be chosen later. With regard to the choice of this fourth unit, the IEC asked the advice of the international organizations dealing with weights and measures. The prevailing opinion was that the connection between electrical and mechanical units should be made by assigning a value for the permeability of space. If the IEC insisted upon choosing one of the practical electrical units as a basis for the system, it should preferably be the ampere defined in terms of the force between parallel conductors. (A full discussion of this question was published in the December, 1935, issue of *Electrical Engineering* by Prof. A. E. Kennelly, American member of the International Committee on Weights and Measures.)

An Advisory Committee on Photometry was appointed, including representatives of the national laboratories of France, Germany, Great Britain, Japan, U. S. S. R., and the United States, and four members appointed as individuals from France, Germany, Holland, and Italy, respectively. This committee is not expected to meet until 1937.

CHANGE OF VOLUME OF RUBBER ON STRETCHING.

When rubber is stretched isothermally at ordinary temperatures the volume remains constant at low elongations, but as the stretching is continued a critical point is reached at which the volume begins to decrease. Above this point, the greater the elongation, the more rapidly does the volume decrease. When a sample is held at a definite elongation above the critical point it may be observed that the shrinkage in volume is not an instantaneous process but proceeds at a diminishing rate with time. An investigation is now in progress at the Bureau in which precise measurements are being made of the change of volume in relation to the elongation, the temperature, and the time during which the rubber is kept stretched.

The critical elongation at which the volume of the rubber begins to change is greater the higher the temperature. At 0° C. it is approximately 200 per cent.; at 25°, 400 per cent.; at 60°, 500 per cent.; while at 70° C. no change of volume was observed for elongations up to 600 per cent.

Experiments with samples of rubber stretched to definite elongations have been conducted for periods of several weeks without reaching a constant volume. Typical results on one sample of rubber stretched to 600 per cent. elongation at 25° C. and maintained in this stretched condition at 25° C. are as follows:

Time.	Relative Volume.
Before stretching	1.0000
After stretching 5 sec.	0.9935
30 sec.	.9912
1 min.	.9901
1 hour	.9881
1 day	.9865
7 days	.9852
21 days	.9847

The volume at the end of three weeks was still changing a little from day to day, and it appears that a very long time would be required for the limit to be reached. The present data do not suffice for any reliable estimation of the limit by extrapolation.

Experiments were also conducted to determine the effect of changing the temperature of stretched rubber. The results showed that the volume coefficient of expansion of the stretched rubber is greater than that of the unstretched. They also indicated that the behavior of stretched rubber is dependent in large measure on the temperature at which it is stretched. For example, a sample of rubber stretched at 25° and cooled to 0° C. exhibits very different behavior from one initially stretched at 0° C.

Most of this investigation is being conducted with soft, vulcanized rubber made according to simple formulas such as the following:

Ingredient.	Parts by Weight
Rubber	100
Sulphur	2
Zinc oxide ("Kadox")	1
Mercaptobenzothiazole	1
Stearic acid	1

When rubber compounds containing fillers are stretched the decrease in volume of the rubber phase may be masked by a large increase in volume resulting from the formation of vacuoles around the filler particles.

SHOE ENDURANCE MACHINE.

Tests which simulate service conditions are being used to an ever-increasing extent in up-to-date laboratories, because, after all, the way a product stands up under conditions of actual use is what the average purchaser is interested in. The chemical composition of the material or even its physical properties are matters of but little moment, provided the service which the product renders is satisfactory. In the development of these newer methods of testing the Bureau has played an important part. It was natural, therefore, that the General Federation of Women's Clubs should seek the assistance of the Bureau in the working out of service tests

and in the preparation of specifications for such things as shoes and hosiery.

A machine for testing the wearing quality of hosiery was designed and constructed at the Bureau over two years ago (Technical News Bulletin 202; February, 1934) and has been in practically continuous use.

The latest development is a machine designed by E. L. Wallace of the leather section to measure the wearing qualities of shoes. The machine was designed to imitate to some extent the forces which are applied to a shoe in service. Motion pictures of persons walking were analyzed and served as a guide in working out the motions of the various parts. The machine consists of eight radial cylinders having pistons ground to fit smoothly. These cylinders and their projecting pistons form, in effect, the spokes of a rimless wheel, and the whole is free to rotate about an axis. Four pairs of shoes, fitted to plastic rubber forms are fastened to the movable pistons by adjustable hinged joints. The load applied to each shoe is controlled by an adjustable compression spring within the cylinders. An endless belt is driven across a bed of rollers by a motor and gear reducer and the radial cylinders are caused to rotate by contact of the shoes on the belt surface. In operation the heel of one shoe first comes in contact with the belt and as it travels along the sole and heel both press on the belt surface. The load on the shoe gradually increases and is at a maximum when the piston is perpendicular to the belt surface. As the shoe travels farther the load gradually decreases, the heel leaves the belt, and the toe is flexed somewhat as in walking. The shoes are run against a cord rubber belt to minimize any wear on the soles, since the test is primarily intended to show comparative endurance of the shoe upper leather, linings, stitches, and heels.

Preliminary tests are now being run on the machine, and so far the results are very promising since they check closely those obtained in actual service.

TRANSPARENT PLASTICS FOR AIRCRAFT WINDOWS.

Although no organic plastic has yet been developed that possesses both the qualities and the low price of glass, never-

theless, such plastics are now serving as windows on many airplanes. Two properties of fundamental importance in the use of transparent materials on aircraft, namely, weight and flexibility, have brought about this invasion of a field generally limited to glass. The organic plastics are approximately one-half as heavy as glass, which is a distinct advantage for aeronautical purposes. Plastic materials can be made up in sheets which are flexible and can, therefore, be readily fitted into openings in curved surfaces. Such inclosures offer considerably less wind resistance than the flat faces ordinarily required when glass is used.

The flexible plastics now in use, however, lack the weathering and scratching resistance characteristic of glass. Recognizing that there is a real need for an improved flexible aircraft window material, the Bureau, in coöperation with the National Advisory Committee for Aeronautics, is studying the suitability of transparent plastics for this purpose. All commercially and experimentally available synthetic resins and cellulose derivatives will be examined to determine their transparency; resistance to surface abrasion; flexibility; impact strength at high and low temperatures; resistance to deterioration by heat, cold, and sunlight, and to the action of water, gasoline, soap and similar materials; dimensional stability; flame resistance; and related properties. Such a comprehensive study may lead not only to further improvement of the flexible plastics now in use, but also to the development of other transparent materials which will be suitable for aircraft windows.

COMPRESSIVE STRENGTH OF MOLDING SANDS.

Members of the Committee on Molding Sand Research of the American Foundrymen's Association, together with several sand producers, have raised some interesting questions regarding the equipment and methods of test used in measuring the compressive strength of molding sands. It has been pointed out repeatedly that variations in length between the tolerance limits will affect strength measurements made on cylindrical specimens of molding sands. The method of preparing the specimen and the condition of the specimen container will also affect the results.

The Bureau has for some time recognized these difficulties in its work on the testing of molding sands. In coöperation with a subcommittee of the Committee on Molding Sand Research, an investigation is planned at the Bureau in order to determine the importance of the various factors that influence the results of the strength test. An analysis of the problem has been made and several changes are being suggested in the standard testing procedure to insure more uniform and consistent results. Proper maintenance of all testing equipment and careful laboratory technique will be essential in order to obtain accurate and reliable results.

CRACKING OF DIESEL ENGINE PISTON IN SERVICE.

A recent metallurgical examination at the Bureau of a large Diesel engine piston that had cracked in service has proved very informative. The piston, a hollow steel casting with a wall thickness of about 2 inches, contained numerous cracks on the inner wall, one of which extended entirely through the wall and through which the piston-cooling liquid had leaked into the cylinder, as well as a number of cracks on the outer wall.

All of the cracks showed, unmistakably, fatigue characteristics which was evidence that they had formed under the action of repeated stresses which were associated, most probably, with the reciprocating motion of the piston. The fatigue action of the repeated stresses was accentuated by the extremely rough inner surface of the piston but this effect was overshadowed by the much more serious effect of corrosion, evidence of which was found in corrosion pits on the inner surface in the area where the fatigue cracks were localized. As is now well recognized, the simultaneous action of repeated stress and of corrosion results in fatigue cracks in metals at stresses very much below the fatigue limit as ordinarily determined. The failure of the piston was clearly a case of corrosion-fatigue.

DURABILITY OF LICENSE PLATE COATINGS.

During the past month the Bureau's accelerated weathering apparatus has been employed to determine the compara-

tive durability of the automobile plate coatings used during the years 1934, 1935, and 1936 by the State of South Carolina.

The plates for 1934 and 1936 have a yellow and black color scheme while for the 1935 plates the color scheme is black and white. The last has proved to be the poorest of the plates. After two weeks in the accelerated test the white coating was chalking badly and rust began to show through. The yellow and black coatings, on the other hand, were in perfect condition. This confirms previous findings of the Bureau.

REFLECTANCE STANDARDS FOR ENAMELS.

In Technical News Bulletin 217 (May 1935), an item on the above indicated subject pointed out some of the causes of discrepancies between reflectance readings obtained in different laboratories, and stated that the Bureau was cooperating with the Porcelain Enamel Institute in developing standard tests, having recently begun work on the reflectance test. Since that time a number of sets of standard reflectance plaques, each set having a total of ten calibrated areas, have been sent to laboratories which have coöperated in this undertaking. It is planned that additional sets of enameled plaques will be calibrated as reflectance standards for those who desire them, upon payment of a fee. The use of these comparison standards, covering a range of reflectance from 50 to 87 per cent., constitutes a major step in bringing reflectance readings obtained in different laboratories to a common basis.

A procedure of test, which includes the method of measuring reflectance that is to be considered as standard, and a method of analyzing reflectance data to obtain the two fundamental reflectance constants of enamels, has been submitted to the Porcelain Enamel Institute and on November 12 was adopted by vote as a tentative standard. The adopted standard also specifies a basis for classifying commercial enamel frits according to their reflectance characteristics, and is expected to be published in the near future as a pamphlet of the Porcelain Enamel Institute.

COLD-SETTING REFRACTORY CEMENTS.

Cold-setting refractory cements are a comparatively new addition to the refractories field and since their consumption has increased rapidly during the past 10 years, a real need for this material apparently exists. A cold-setting refractory cement, as its name implies, will set up or harden without the application of heat, and at the same time because of its refractory ingredients will form a ceramic bond at high temperatures. The ability of a cement to develop and retain strength over a wide temperature range is a very desirable asset since it may then be used in all parts of a furnace installation without danger of any of the refractories working loose during operation of the furnace.

The necessity for evaluating certain properties of these cements is evident in order to aid the consumer to choose those most suitable for his purpose. The Bureau has undertaken a study with that end in view and has obtained results in preliminary tests which show that the bonding strength of a cement is dependent on the type of fire-clay refractory with which it is used. For this purpose four different types of cold-setting fire-clay cements received in the wet condition were studied with respect to water content, drying shrinkage, particle size, pyrometric cone equivalent (softening point), and transverse strength. Also, five brands of fire-clay brick were studied with respect to rate of water absorption and transverse strength. The unheated bonding character of each of the four cements was obtained with each of the five brands of brick by joining the 2½ by 4½ inch faces of two half bricks, using a 1/16 inch mortar joint. After drying, the strength of the joint was found by breaking the bonded brick transversely.

The transverse strength of the bricks ranged from 440 to 2,665 lb./in.^{2} and the total water absorption from 1.5 to 14.6 per cent. The transverse strength of the cements ranged from 900 to 3,415 lb./in.^{2}, the water content from 22.5 to 25.8 per cent., the drying shrinkage from 2 to 8 per cent., the sieve analysis showed from 0 to 15 per cent. retained on a No. 60 U. S. Standard sieve, and the pyrometric cone equivalent ranged from 27 to 31–32. The results obtained indicate that the bonding strength of the cement is greatly influenced by the

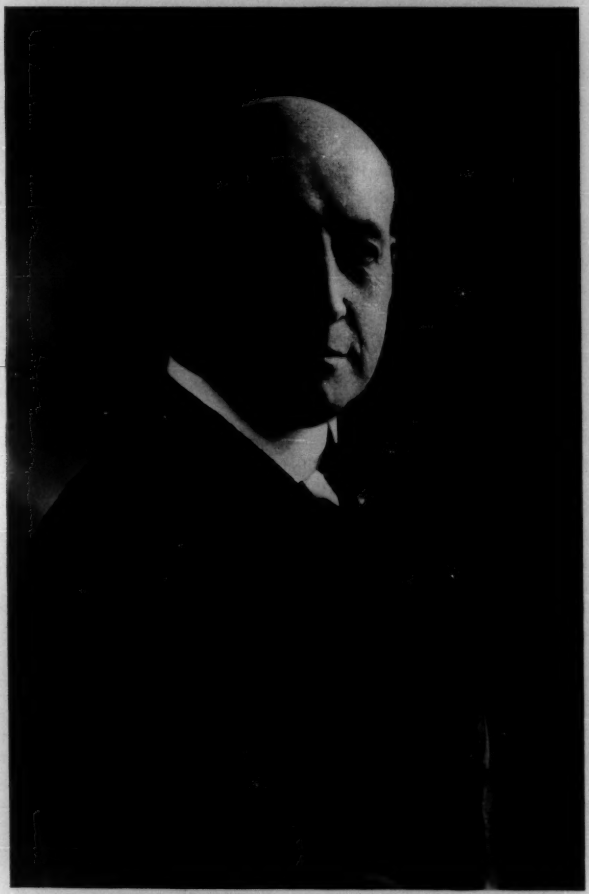
type of brick with which it is used. In other words, if the cement properly bonds with the bricks, the strength of the joint varies with the strength of the brick and also with the rate of water absorption. As an example, the same cement when used with each of five different brands of brick showed a bonding strength ranging from 190 to 630 lb./in.^{2}. This information leads to the conclusion that some consideration must be given to the type of brick when a requirement for bonding strength is included in a specification for cold-setting refractory cements.

EFFECT OF REPEATED FREEZING AND THAWING UPON THE PORE STRUCTURE OF BRICK.

In the study of pore structure of structural clay products and its relation to the resistance to disintegration by weathering agencies, repeated freezing and thawing tests are being made on medium hard and soft brick to determine the effect of such treatment upon pore structure. The brick are soaked in water for 48 hours, frozen, thawed in tap water, and dried to constant weight at 110° C. for each cycle, and the dry weight, bulk volume, solid volume, porosity, density, water absorption, and air permeability are determined for each cycle. Inasmuch as the permeability indicates that the flow of air through the specimen follows the law of capillary flow, the porosity equivalent in uniform capillaries of radius "R" and number "N" are calculated from Poiseuille's formula for comparative purposes between different cycles.

The results of repeated freezing, thawing, and drying indicate that the bulk volume and absorption remain substantially unchanged, the weight, solid volume, permeability and capillary radius "R" increase and the porosity, density and number of capillaries N decrease.

The increase in permeability and increase in "R" indicate that the pores or connecting passages between them are being enlarged, and the decrease in porosity, increase in weight, and decrease in both density and "N" indicate that water is being taken up by minute pores which may be due to freezing pressure, and is held with such tenacity that it is not expelled during drying at 110° C.



HOWARD McCLENAHAN
E.E., LITT.D., D.ENG., D.SC., LL.D.
Secretary—Editor—Director
1925–1935

THE FRANKLIN INSTITUTE.

HOWARD McCLENAHAN
1872 1935

It is with the deepest sense of loss and sorrow that we report to the membership of the Institute the death of our Secretary and Editor, Howard McClenahan. He was also, until October 1935, Director of the Museum.

When, in 1925, it became necessary to select a Secretary for the Institute, the late Dr. Eglin, who was then President, went to Princeton and urged his friend Howard McClenahan to undertake the work. The Institute enjoyed an international reputation, and there was opportunity for constructive development of its activities. The offer was accepted.

Dr. McClenahan was a man eminently fitted for the position. Because of his long association with Princeton, and the notable work he had done there both as professor and administrator, he was recognized as one of the leading educators of the country. For many years he had been Professor of Physics, and for thirteen years had served as Dean of the College. His sound learning, fearlessness and insight made him respected and admired; his patience, understanding, sense of fair play and humor had endeared him to many. By broad acquaintance with the scientific world, by reputation, experience and native gifts, he was exceptionally well equipped for the new endeavor.

Dr. McClenahan came to Philadelphia in 1925 and took up his duties in the old building of the Institute on Seventh Street. In his first year he established what he called "Medal Day," and in succeeding years developed this occasion until it is now regarded as an outstanding event in scientific circles. It is an occasion designed to do honor to those who are selected by the Institute for the award of medals.

The James Mapes Dodge Lecture Foundation for young

people was established under Dr. McClenahan's guidance; the JOURNAL of the Institute was given new form and broader content; the scope of the weekly lectures was widened; by reason of his acquaintance with educational circles he was able to summon many persons of distinction to talk in the Hall of the Institute.

The construction of the Bartol Research Laboratory upon a new site at Swarthmore, the removal of the plant from the old site at Nineteenth Street and the Parkway, and problems incident to this important development in the field of research occupied much of the Secretary's time and thought during the years between 1927 and 1930.

By reason of his training, Dr. McClenahan was keenly interested in the educational functions of the Institute, and early sought for means of development in this direction. He became convinced of the educational value of the technological museum, developed in Europe but not generally known in this country. He presented his views to the Board of Managers, and obtained authority to study at first hand the museums in London, Paris and Munich. Upon his return he presented the project for a museum of this type with such interest and enthusiasm that he was accorded the wholehearted support of the Board.

The new Museum building on the Parkway represents in tangible form the vision that he had. It was built with money received from loyal Philadelphians who were eager to establish a lasting memorial to Benjamin Franklin. Splendid contributions by the late Cyrus H. K. Curtis, Samuel S. Fels and others, the public support elicited by the efforts of the Benjamin Franklin Memorial, Incorporated, sponsored by the Poor Richard Club, the coöperation of City Councils, were all essential factors in the accomplishment of the final result. Upon Dr. McClenahan, however, fell the heavy burden of coördinating the efforts of all those who so finely contributed to the success of the enterprise. He worked indefatigably to add this unique instrumentality to the educational resources of the city.

The construction of the building was but one part of the work involved. Exhibits were required of a kind that would serve an educational purpose and of a type that would appeal

to the imagination of the public. The organization of technical and administrative staffs was necessary. There was a bewildering variety and volume of work calling for scientific knowledge, imagination and constructive ability of high order. Philadelphia has to-day the best equipped scientific museum in the country, with the largest collection of exhibits housed under one roof.

Although Dr. McClenahan's work at The Franklin Institute was largely administrative, he maintained a lively interest in all educational and cultural activities.

He was a member of the Board of Public Education of Philadelphia and Associate Trustee for Graduate Study at the University of Pennsylvania. He was also honored by election to membership in the American Philosophical Society, the Royal Institution of Great Britain and in the Board of Directors of the Deutsches Museum (Munich). His learning and achievements received general recognition both here and abroad, and he was the recipient of many honorary degrees.

Dr. McClenahan had unique ability to attract people to him. He demanded nothing and seldom lost his cheerful serenity. The integrity of his character and the clarity of his thought and expression created confidence. His geniality, his warm human interest and kindly sense of humor engendered affection. To all who knew him his death has brought the grief of personal loss. The Institute will long feel the absence of his wisdom and his loyal devotion to its interests.

ANNUAL MEETING, JANUARY 15, 1936.

The annual meeting of The Franklin Institute was held on the evening of Wednesday, January 15th, in the lecture hall of the Institute. The meeting was called to order at 8:15 o'clock by the President, Mr. Nathan Hayward.

The first item of business was the result of the annual election. The report of the tellers indicated that the following gentlemen were duly elected:

President (To serve one year)	Nathan Hayward
Vice-Presidents (To serve one year)	Henry Howson
	Walton Forstall
	W. Chattin Wetherill
	S. S. Fels
Treasurer (To serve one year)	Benjamin Franklin

Managers (To serve three years).....Edward G. Budd
Clarence A. Hall
George A. Hoadley
A. Atwater Kent
O. J. Matthews
George Wharton Pepper
James S. Rogers
Richard W. Lloyd
(To serve one year).....Irenee DuPont

The Chairman invited a motion to adopt the report. This was offered and seconded and the individuals named were declared elected to the offices indicated.

It was also announced that the minutes of the December meeting had been published in full in the JOURNAL of the Institute for January, and as there were no corrections or objections, the Chairman declared the minutes approved.

The additions to the membership since the last report were as follows: Institute members—114, Museum members—695.

The Chairman also announced that the Two Hundredth Anniversary of the birth of James Watt would be observed on January nineteenth, twentieth and twenty-first. Beginning on Sunday afternoon at 12:30 o'clock there will be an international broadcast from the Science Museum of South Kensington, London, and from The Franklin Institute. The program for Monday is scheduled at the Lehigh University, Bethlehem, Pa. On Tuesday afternoon there will be an exhibition and demonstration at The Franklin Institute and a meeting of the Newcomen Society of England will be held at 2:45 P.M. A formal dinner at the Bellevue-Stratford Hotel on the same evening will conclude the ceremonies. Members of the Institute and others are invited to attend.

The Chairman then introduced Dr. Arthur L. Day, Director, Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C., who addressed the meeting on "Recent Earthquakes and Their Interpretation." The speaker referred to the development in seismographs and described the newer types, which, with their increasing range and power, have brought to light new types of earth movement which were hitherto little known. These movements appear to have their origin from 300 to 700 kilometers below the surface of the earth.

There have also been destructive earthquakes during recent months in regions of considerable population. Quite recently also many of us have had opportunity to feel earth movements beneath our feet in the stable regions of the Eastern States. Very recently also serious earthquake disturbances have accompanied decaying volcanism on the Island of Montserrat. These various types of earth movements, together with some of the newer types of seismologic recording apparatus, were discussed.

The subject was illustrated by many colored lantern slides of earthquake destruction in Southern California, and more recently in Helena, Montana.

The paper was followed by a discussion, in which Drs. Henderson, Piccard, Swann and others participated. The President extended the thanks of those present to Dr. Day and the meeting adjourned at ten o'clock.

HENRY BUTLER ALLEN,
Secretary.

COMMITTEE ON SCIENCE AND THE ARTS.

(Abstract of Proceedings of Stated Meeting held Wednesday, January 8, 1936.)

HALL OF THE COMMITTEE,
PHILADELPHIA, JANUARY 8, 1936.

MR. CHARLES H. MASLAND, 2D, *in the Chair.*

The following reports were presented for final action:

No. 2990: The Determination of Gravity at Sea.

This report recommended the award of the Howard N. Potts Medal to Dr. F. A. Vening Meinesz, of the Netherlands Geodetic Commission, "In consideration of the outstanding value of his work in geodesy; and the energy, originality, and skill he has shown in the development and use of apparatus for determining gravity at sea."

No. 3009 } The Standing Committee on The Franklin Medal presented
No. 3010 } its report.

This report recommended that two Franklin Medals be awarded in 1936; one to—

Dr. Frank Baldwin Jewett, of New York City, "In recognition of his many important contributions to the art of telephony, which have made conversation possible not only from coast to coast, but from this country to the other side of the world—contributions of which some were made by him alone, and some by him in collaboration with other workers in the great laboratory of research which he organized and which he has directed with such signal success";

and one to—

Charles Franklin Kettering, of Detroit, Michigan, "In recognition of his significant and timely contributions to the science of automotive engineering—a science out of which has grown the greatest industry in this country, whose manufactured product has in only a quarter of a century changed the face of the civilized world."

GEO. A. HOADLEY,
Secretary to Committee.

LIBRARY NOTES.

RECENT ADDITIONS.

Beilstein's Handbuch der organischen Chemie, Vierte Auflage. Zweiundzwanzigster Band. 1935.

Chemical Engineering Catalog. Twentieth Annual Edition. 1935.

EUKLID. Die Elemente. Nach Heiberg's Text aus dem Griechischen übersetzt und herausgegeben von Clemens Thaer. 3 Teil. 1935.

GROUME-GRJIMAILO, W. E. The Flow of Gases in Furnaces. Translated from Russian into French by Leon Dlougatch and A. Rothstein. Translated from the French by A. D. Williams with an Appendix upon the Design of Open-Hearth Furnaces. 1922.

KNIGHT, BERNARD H. Road Aggregates: Their Uses and Testing. 1935.

Newcomen Society for the Study of the History of Engineering and Technology. Extra Publication no. 3: Aeronautical and Miscellaneous Note-Book (ca. 1799–1826) of Sir George Cayley. 1933.

Photograms of the Year 1936. The Annual Review of the World's Pictorial Photographic Work. Edited by F. J. Mortimer. No date.

Sugar Reference Book and Directory. 1935.

WIEN, W., AND F. HARMS. Handbuch der Experimentalphysik. Band 11, 2 Teil. 1935.

BOOK REVIEWS.

DIE UNWANDLUNGEN DER CHEMISCHEN ELEMENTE, von Arthur Haas. 118 pages, illustrations, tables, 15 × 23.5 cms. Berlin und Leipzig, Walter de Gruyter & Company, 1935.

Developments from pure research in recent years have revealed much new knowledge. It is a matter of fact that the extent of this new knowledge creates a need of those not immediately associated with pure research to a means of availing themselves of opportunity to become familiar with what may revolutionize basic physics and chemistry. To fill such a need is the purpose of this booklet. It consists of a series of five lectures in understandable form aimed at those readers generally familiar with modern physics. The booklet divisions are: (1) Die Materialisation des Lichtes, (2) Die Grundstoffarten, (3) Die Mittel der Atomzertrümmerung, (4) Die Ergebnisse der Atomzertrümmerung and (5) Die künstliche Radioaktivität.

The booklet is well illustrated and well written. Particular mention should be directed to the back where can be found reference notes from each lecture. These should assist the reader materially in grasping the subject.

R. H. OPPERMANN.

A TREATISE ON HEAT (INCLUDING KINETIC THEORY OF GASES, THERMODYNAMICS AND RECENT ADVANCES IN STATISTICAL THERMODYNAMICS), second and revised edition of A Text Book on Heat, by M. N. Saha. 815 pages, plates, tables, 17 × 25 cms. Allahabad and Calcutta, The Indian Press, Ltd., 1935.

This is the second and revised edition of the author's Text Book of Heat. Those who are familiar with the first edition can best visualize the detailed completeness and clarity of the treatment. Revisions have been made in incorporating new results as far as practicable, in changing and making more clearer presentations, and in presenting new material.

To those who have not had the opportunity of becoming familiar with the first edition it can be said that the present volume contains a remarkably thorough advanced course in the subject. The authors are men of wide experience in teaching and in research and, as will be seen on examination of this book, most successful expositors of the subject.

There are nineteen chapters to the book covering some 728 pages and appendices containing notes illuminating and further explaining data referred to in the text. Roughly, it may be divided into two parts. The first part begins with thermometry and calorimetry, gases, the production of low temperatures which gives an account of the recent methods of approaching the absolute zero, to a

chapter on the theory of heat engines. This chapter can be taken as the beginning of the second part of the book—thermodynamics. Similar to the first part of the book, this part starts where elementary studies on the subject end and covers steam engines, internal combustion engines, and steam turbines. From here the reader is taken through the laws of thermodynamics, thermodynamical equilibria, statistical thermodynamics and dissociation equilibria. In relation to the treatment on dissociation equilibria, the authors state that use has been made of investigations on molecular spectra, this being unavoidable. They feel that in the future, all advanced books on Heat must make increasing use of knowledge of molecules derived from spectroscopic data. The last chapter is devoted to new methods in statistical thermodynamics. Here a full account is given of B.E.- and F.D.-statistics. One of the notes in the appendix above referred to incorporates the application of wave-mechanics to thermodynamics and includes a sketch of Dirac's proof that thermodynamical assemblies would obey either the B.E.- or the F.D.-statistics.

The book has been prepared with great care. Its construction is such as to pass in logical sequence from one topic to another as much as is possible. The prerequisites for its most efficient use are college physics and mathematics. As a text for an advanced course and as a reference and information book for research workers in physics, physical chemistry, and astrophysics, it is highly recommended.

R. H. OPPERMANN.

BIOLOGY FOR EVERYMAN, by J. Arthur Thomson, M.A., LL.D., Regius Prof. of Natural History, Aberdeen, 1899–1930. Vols. 1 and 2, illustrations, 13 × 20.5 cms. New York, E. P. Dutton & Co., Inc., 1935. Price $5.00 complete.

Two books such as these two volumes are a monument to the scholarly life of a great man. The wealth of information that they contain for the lay reader, the abundant illustrations all testify to a splendid purpose of the author and the late Mr. J. M. Dent, namely to make the world of biological science available for Everyman.

The first volume leads the reader through the beginning of life up to the gorilla. The second book deals with animal life in general. Book III the plant world and book IV Man. The last three books make up the second volume.

A great deal of credit is of course due to the editor, E. J. Holmyard, M.A., M.Sc., D.Litt., F.I.C. Considering the material to be covered and the many illustrations to be shown, the close set type and crowded format are justified if we bear in mind the use through the public libraries to which these two volumes will be put.

They are grand books for the boy who is in the blotter stage of intellectual development. The chances are that "dad" will borrow them for a little belated reading on his own.

H. W. ELKINTON.

THE ERUPTION OF MT. PELEE, 1929–1932, by Frank A. Perrett. 126 pages, illustrations and chart, 23 × 29.3 cms. Washington, Carnegie Institution of Washington, 1935.

Ever since the sunsets of the summer of 1902 Martinique and particularly Mt. Pelee have been an object of my wonder and curiosity. The terrific explosion May the 8th not only destroyed the town of St. Pierre, the people therein, and the

ships in the harbor, except "Roddam" of Scruttons, but it flung into the upper air an abundance of fine volcanic ash. It was this ash, these minute particles that made glorious sunsets which some who read this review may still recall. It was this eruption that attracted Frank A. Perret to a career with volcanoes.

Frank Perret has not concerned himself much with the repercussions of this fateful disaster. His purpose has been the study of volcanology. His study has been very well illustrated with many plates which give the reader a splendid idea of the terrain but also by their series show changes of cone and dome and nuée ardente so that one can gain a good idea of the way a volcano behaves.

The eruption of 1929–1932 is diagnosed and the record of prediction is most interesting. From general phenomena he leads into detailed observations of the crater, lava, domes and spines, seismic effects and the many other things that are to be considered by careful students of volcanoes.

There are two sections that bear special note. The discussion of the nomenclature of volcanology shows how this science is in the early stages of its development. The field work is usually on a Cyclopean scale so that few can get close enough to a volcano to know it intimately. The data has been harvested under real handicaps. Man still looks upon an active volcano as a profound mystery. As fireworks they are magnificent and awful. The full discussion of nuées ardentes is, to my mind, one of the most informing sections of the book. These spectacular clouds composed of ash and gases have been measured for temperature, sound, weight, electrical effects and other manifestations that make them so important a phase of volcanism. Perret pleads for an embryonic station on Morne Lénard where turrets and subterranean galleries would make it possible to become better informed. These nuées ardentes sweep by this post so that students would have splendid opportunities of study.

From the beginning to the last chart of the appendix this publication will hold the grateful attention of the volcano addict.

H. W. ELKINTON.

GENERATION OF THE UNIVERSE AND "DESIGN FOR LIVING," by Percy A. Campbell. 101 pages, 14 × 20.2 cms. Cleveland, The Caxton Company, 1934. Price $1.50.

It is a little late to refer to this "design" book. One is not quite sure on reading it whether the author has designs on his readers or himself. The title page starts off with the pattern of a snow crystal and the briefism "nature geometrizes."

The book has a noble dedication to the inseparable twinship of Being and Non-being. By the end of chapter two it is necessary to pinch oneself to be perfectly sure that one is alive after following Campbell's comment on a Relativistic Universe and a subtle substitution of Hegel's doctrines of being for Schopenhauer's universe of being *or* non-being. The *or* is very important—with each man pulling on his end.

There is a note of self-assurance on page 38:

> "Thus the universe is naturally self-existing, or self-generating, complete unit-entity. The points-natural self-exist or self-generate themselves only in mutual relationship with one another. The mutuality of points-natural is the grand determinant of the universe itself, as the one and sole true natural."

After passing to the mutuality of naturals, matter as a mode space, a system of spacewarps we arrive at consciousness as cerebration. This is not quite the case because the reader will come to a full stop at chapter fourteen "Design for Living." Herein lies the best part of the little volume. Campbell forecasts a race giving more and more attention to life here and now, the elimination of excessive riches, sub-types, the maintenance of an even quality by birth-control and the development of a single world language. (English just missed it according to Campbell.) He is fond of the poets to the last. To quote Goethe (page 97):

"Only he deserves life and freedom who is forced daily to win them afresh."

H. W. ELKINTON.

PUBLICATIONS RECEIVED.

The Next Hundred Years, by C. C. Furnas, 434 pages, 14.5 × 22.3 cms. Baltimore, The Williams & Wilkins Company, 1936. Price $3.00.

An Outline of Probability and Its Uses, by Maurice C. Holmes, 119 pages, illustrations, tables, 13.8 × 21 cms. Ann Arbor, Edwards Brothers, Inc., 1936. Price $1.50.

Einführung in die angewandte Akustik, insbesondere in die neueren Probleme der Schallmessung, Schallübertragung und Schallaufzeichnung, von Dr. H. J. Von Braunmuhl und Walter Weber, 216 pages, illustrations, tables, 15.8 × 23.4 cms. Leipzig, S. Hirzel, 1936.

Short Wave Radio Handbook, by Clifford E. Denton, 127 pages, illustrations, tables, 16.6 × 21.5 cms. New York City, Radio and Technical Publishing Co. Price $1.00.

Radio Physics Course, an elementary text book on Electricity and Radio, by Alfred A. Ghirardi, E.E., 972 pages, illustrations, tables, 17 × 23 cms. New York City, Radio and Technical Publishing Co., 1933. Price $4.00.

Solubility of Non-Electrolytes, second edition, by Joel H. Hildebrand, Ph.D., 203 pages, illustrations, tables, 16 × 23.5 cms. New York, Reinhold Publishing Corporation, 1936. Price $4.50.

Amateur Telescope Making—Albert G. Ingalls, editor, with 13 collaborators, 498 pages, illustrations, 14.5 × 19.8 cms. New York, Munn & Co., Inc., 1935.

Canada Department of Mines, Laboratory Tests on Structural Assemblies of Brick and Tile, by L. P. Collin, 33 pages, plates, illustrations, tables, 16.5 × 25 cms. Ottawa, King's Printer, 1935. Price 10¢. *Wood Fuel Burning Tests*, by E. S. Malloch and C. E. Baltzer, 4 pages, plate, illustrations, tables, 16.5 × 25 cms. Ottawa, King's Printer, 1935. Price 10¢.

Bell Telephone Laboratories, Monograph B–886, Circulating Currents and Singing on Two-Wire Cable Circuits, by Leonard Gladstone Abraham, 32 pages, illustrations, tables. B–887, Transatlantic Long-Wave Radio Telephone Transmission, 1923–1933, by Austin Bailey and Howard M. Thomson, 18 pages, illustrations, tables. B–888, Aspects of Low-Frequency Induction Between Power and Telephone Circuits, by H. R. Huntley and E. J. O'Connell, 27 pages, illustrations. B–889, Further Extensions of the Theory of Multi-Electrode Vacuum Tube Circuits, by S. A. Levin and Liss C. Peterson, 14 pages, illustrations. B–890, Operation of Ultra-High-Frequency Vacuum Tubes, by F. B. Llewellyn, 34

pages, illustrations. B–896, Newer Concepts of the Pitch, Loudness, and Timbre of Musical Tones, by Harvey Fletcher, 25 pages, illustrations, tables. B–898, Heat Treatment of Magnetic Materials in a Magnetic Field—I, by Joy F. Dillinger and Richard M. Bozorth, 11 pages, illustrations, tables. B–899, Heat Treatment of Magnetic Materials in a Magnetic Field—II, by Richard M. Bozorth and Joy F. Dillinger, 12 pages, illustrations. George A. Campbell, A Resume of His Technical Contributions to Telephony, by F. B. Jewett, 20 pages, illustrations, 9 pamphlets, 15 × 23 cms. New York, Bell Laboratories, 1935.

National Advisory Committee for Aeronautics, Technical Notes, No. 549. Drag of Prestone and Oil Radiators on the YO–31A Airplane, by S. J. DeFrance, 3 pages, plates, illustrations, 20 × 26.5 cms. Washington, Committee, 1935.

THE FRANKLIN INSTITUTE

OFFICERS FOR 1936

President ..... NATHAN HAYWARD
Vice-presidents ..... HENRY HOWSON, SAMUEL S. FELS, WALTON FORSTALL, W. CHATTIN WETHERILL
Secretary and Director ..... HENRY BUTLER ALLEN
Assistant Secretary and Librarian ..... ALFRED RIGLING
Treasurer ..... BENJAMIN FRANKLIN
Assistant Treasurer ..... MARSHALL S. MORGAN
Controller ..... WILLIAM F. JACKSON, JR.

Board of Managers

HENRY BUTLER ALLEN
GEORGE H. BENZON, JR.
EDWARD G. BUDD
FRANCIS T. CHAMBERS
G. H. CLAMER
IRENEE DUPONT
WILFRED W. FRY
W. H. FULWEILER
ARTHUR W. GOODSPEED
CLARENCE A. HALL
GEORGE A. HOADLEY
A. ATWATER KENT
L. H. KINNARD
HORACE P. LIVERSIDGE
MALCOLM LLOYD, JR.
RICHARD W. LLOYD
CHARLES H. MASLAND, 2ND
O. J. MATTHEWS
CHARLES PENROSE
GEORGE WHARTON PEPPER
JAMES S. ROGERS
SAMUEL M. VAUCLAIN

Scientific Staff

Associate Director ..... JAMES BARNES
Associate Director—Astronomy ..... JAMES STOKLEY
Associate Director—Aviation ..... C. TOWNSEND LUDINGTON
Associate Director—Graphic Arts ..... RUSSELL L. DAVIS
Associate Director—Chemistry ..... N. H. SMITH
Associate Director—Medicine ..... SYDNEY L. WRIGHT
Associate Director—Music ..... GUY MARRINER

Bartol Research Foundation

Director ..... W. F. G. SWANN
Assistant Director ..... T. H. JOHNSON
Research Fellow ..... W. E. DANFORTH
Research Fellow ..... G. L. LOCHER
Research Fellow ..... C. G. MONTGOMERY
Research Fellow ..... MRS. C. G. MONTGOMERY
Research Fellow ..... L. H. RUMBAUGH
Chief Mechanician ..... ROY VAN VALKENBURGH

The Biochemical Research Foundation

Director ..... ELLICE MCDONALD
Chief Physicist ..... A. J. ALLEN
Chief Chemist ..... E. F. SCHROEDER
Chief Cytologist ..... J. O. ELY